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Oscillations on Electrothermal-Chemical (ETC) Closed-Chamber JA2 Burn-Rate Reductions

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Oscillations on Electrothermal-Chemical (ETC) Closed-Chamber JA2 Burn-Rate Reductions

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Abstract

Closed-chamber electrothermal-chemical firings of JA2 7-perf propellant revealed the presence of oscillations on its burn rates. This study was originated by questions raised about the probable causes for this phenomena. The discussion that follows analyses the fiber-optic links utilized for the data acquisition, the code used to deduce the propellant burn rate and the filtering for data smoothing, and finally, the effect of the plasma injection and its energy. The result of this analysis suggests that the plasma injection contributes to burn-rate oscillations, that their amplitude is proportional to the energy of the plasma injected, and that the oscillations are a function of the closed-chamber pressure.

Acknowledgments

The author extends his thanks to Dr. Douglas E. Kooker, who brought into focus the study of the oscillations observed on the electrothermal-chemical (ETC) closed-chamber burn-rate reductions, as well as for the hints regarding the methodology of the analysis.

The author also wishes to thank Mr. William F. Oberle and Mr. Irvin Stobie for their invaluable insight on the subjects discussed, as well as their helpful suggestions.

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1. Background

Closed-chamber electrothermal-chemical (ETC) firings of JA2 7-perf solid propellant conducted in a 129.4-cm^3 vessel have produced burn rates characterized by the presence of oscillations. A recent ETC closed-chamber temperature sensitivity study on the same propellant (Del Guercio, Stobie, and Oberle 1996a) has shown oscillations on the burn rates for all of the temperatures selected. Burn rates are deduced by the BRLCB code (Oberle and Kooker 1993) and are usually smoothed through a code filter option with a cutoff frequency selected from the inspection of their fast Fourier transform (FFT) amplitude spectrum. A filter option (Vu-point 1991) can also be used to low-pass-filter (LPF) the initial voltage vs. time (v/t) or pressure vs. time (P/t) data, or the burn rate after it is deduced by the BRLCB code. This Vu-point option allows a choice of a larger transition frequency (cutoff frequency) and transition width, which results on deduced burn-rate plots, smooth enough as to allow visual comparisons.

All of the conventional firings, performed with the 129.4-cm^3 chamber up to date, have rendered burn rates that are oscillation-free (independent of what method of filtering was used.) However, oscillations were observed on burn rates from conventional (non-ETC) firings from a larger closed-chamber vessel (200 cm^3). These burn rates were also deduced by the BRLCB code and smoothed through the code's filter option with cutoff frequencies selected from inspection of the FFT amplitude spectrum.

The following discussion considers whether the oscillations observed on the ETC closed-chamber burn rates of JA2 7-perf solid propellant are introduced (a) as a consequence of the input of a spurious signal generated by the data acquisition and fiber-optic link; (b) due to oscillations present on the initial P/t curve; (c) due to filtering done previous to, or after, the burn rates are calculated; or (d) due to the plasma energy, accounted for as an energy file input on the BRLCB burn-rate code calculation.

2. Introduction

To investigate the source for the burn-rate oscillations, a careful assessment of the experimental data acquisition setup, burn-rate smoothing processes, and energy file impact on the burn-rate reduction has to be considered. The fiber optics, which isolate the data acquisition equipment from the high voltages generated by the pulse-forming network (PFN) at the time of the ETC firings, are, however, a source of undesired noise. As the pressure rise caused by the propellant combustion in the closed chamber is detected by Kistler transducers located at the combustion chamber end and on the chamber wall of the vessel, respectively, a signal is transmitted to a charge amplifier through a microdot link. The charge amplifier then sends a calibrated output to the oscilloscope(s) via a fiber-optic link. This configuration, consisting of a transmitter and coupled receiver, has been known to add undesired noise to the recorded signals (Katulka et al. 1993).

As noise generated during the data acquisition process could be related to oscillations on the burn rates, case (a) was addressed by recording a synthetic pressure signal separately through each of the components of the fiber-optic link. Burn rates were then deduced from the simulated P/t curve, generated as a Sin wave output from a Waveteck pulse generator and recorded on a oscilloscope (a-1) without charge amp or fiber optics, (a-2) with charge amp and fiber optics, and (a-3) without charge amp, with fiber optics.

To address case (b), the effect of the presence of oscillations on the initial P/t curve was investigated by adding a code generated small-amplitude Sin wave (Appendix A) to a noise-free P/t signal. The burn rate of the modified P/t curve showed that oscillations that were visually undetected on the initial pressure curve could generate oscillations on the corresponding burn rate (Kooker, Appendix B). The noise-free P/t curve was generated by an "inverse" BRLCB burn-rate reduction option using a JA2 7-perf non-ETC data file. The effects of a high-frequency noise, as well as a random noise signal added to the P/t curve, were also considered by the code, but the result was not related to oscillations.

For case (c), a non-ETC burn rate, deduced from a smoothed (LPF) P/t data set previous to the code reduction, was compared to the burn rate from the same set, smoothed (LPF) after being deduced by the BRLCB code. These burn-rate plots, when compared, were similar and had no oscillations. Also, the ETC burn rate, deduced from a smoothed (LPF) P/t data set previous to the code reduction, was compared to the burn rate from the same set smoothed (LPF) after being deduced by the code. These ETC burn-rate plots were similar and showed oscillations. For non-ETC burn-rate reductions, a visual comparison is possible between nonsmoothed burn rates, smoothed (LPF) burn rates, and smoothed (LPF) burn rates after being deduced. For these cases, the smoothing process clearly did not introduce oscillations.

For ETC burn-rate reductions, this discussion does not attempt to prove that the smoothing process generates oscillations, as it is not possible to establish a visual comparison between nonsmoothed burn rates, initially smoothed burn rates, and burn rates smoothed after having been deduced by the BRLCB code. It did show, however, that the smoothing of the initial ETC P/t data before the code reduction produced the same burn rates as the ones that were smoothed (LPF) after their code generation.

Finally, on case (d), to investigate the possible contribution to oscillations by the plasma itself, burn rates were generated two ways: (d-1) as from an ETC firing reduction by using non-ETC P/t data with the addition of an energy file, and (d-2) as from a non-ETC firing by using ETC P/t data from an ETC firing without including its energy file. These results are discussed.

3. Impact of Data Acquisition and Fiber-Optic Link

On case (a), to determine the level of distortion introduced by the fiber-optic link and its possible relation to the oscillations observed on the deduced burn rates, a simulated P/t curve generated from a Sin wave output of a wave generator was recorded three different ways: (a-1) without charge amp or fiber optics; (a-2) with charge amp and fiber optics; and (a-3) without charge amp, with fiber optics.

Data recorded without the charge amp or fiber optics (case [a-1] Figure 1) shows little noise content. Cases (a-2) and (a-3), with charge amp and fiber optics and without charge amp, with fiber optics, respectively, show data (Figure 1) with a significant noise content. The P/t signal was low-pass-filtered before the burn rates were deduced by the BRLCB code, and the LPF parameters selected for this filter were approximately a 2,500-Hz transition frequency, a 650-Hz transition width, and a maximum response of 0.01 outside the pass band. The deduced burn rates (Appendix C) for cases (a-1), (a-2), and (a-3) do not show any large-amplitude oscillations. The burn-rate calculations were deduced, assuming JA2 propellant, as its rise time to maximum pressure, matched the one of the Sin wave. These burn rates (Figure 2) were deduced, scaling the P/t curves to simulate a maximum pressure of 300 MPa, assuming a propellant loading density of 0.2 (30-g JA2 disks).

4. Impact of Oscillations on Original P/t Curve

The generation of burn-rate oscillations was studied by adding a small-amplitude sinusoidal signal to a P/t curve (Kooker, Appendix B), generated through an inverse BRLCB burn-rate reduction. The signal, "y = NSin(wt)," was added to this noise-free P/t data set through a code (Appendix A). The amplitude selected for the sinusoidal signal was 1/400 of the maximum value of the P/t curve. It was superimposed, making it visually undetected. To be able to reproduce the type of oscillations observed on previous ETC temperature sensitivity study firings (Idents 04125S3 and 04115S1), frequencies of 1.14 kHz and 2.28 kHz were chosen. While the P/t curve shown in Figure 3a remains smooth in appearance for a 2.28-kHz signal, the deduced burn rates clearly show large-amplitude oscillations (Figure 3b). These burn rates, obtained with the 1.14-kHz and 2.28-kHz signals, track Idents 04125S3 and 04115S1, respectively, very closely. Higher values for the frequency selected for the "Sin(wt)" term are reflected in an increase of oscillations for the signal, resulting in the addition of the sinusoidal and P/t signals. This fact suggests that the oscillations are generated during the closed-chamber plasma-injection process and apparently persist to mean maximum pressure on P/t curve.

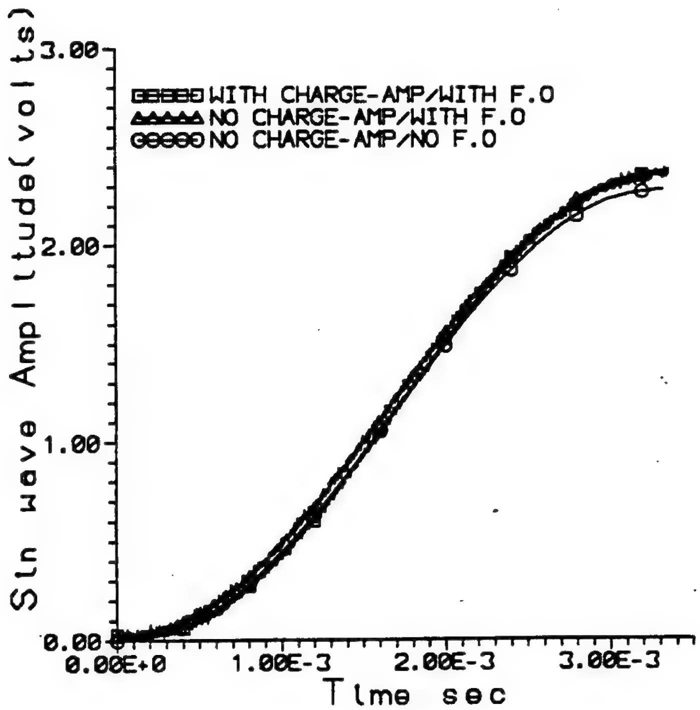

Figure 1. Sin Signal Recorded for Cases (a-1), (a-2), and (a-3).

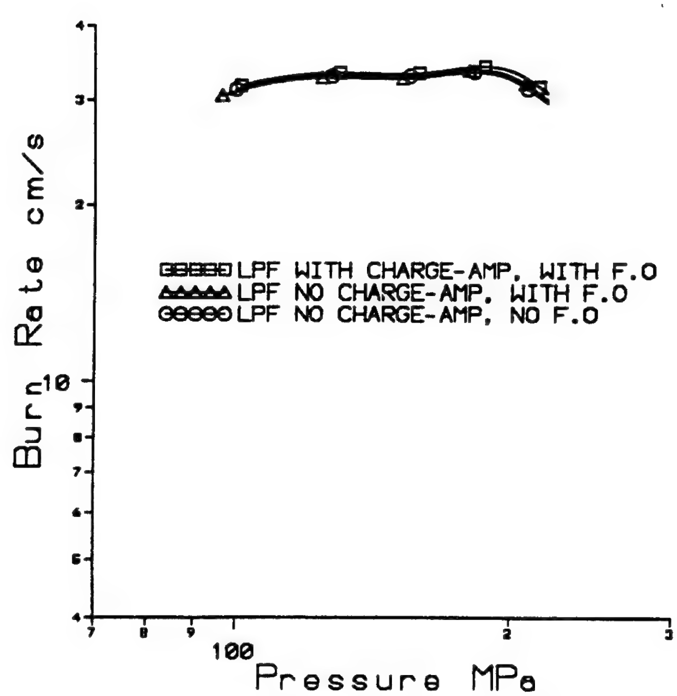

Figure 2. Burn Rates of a Sin Signal Recorded for Cases (a-1), (a-2), and (a-3).

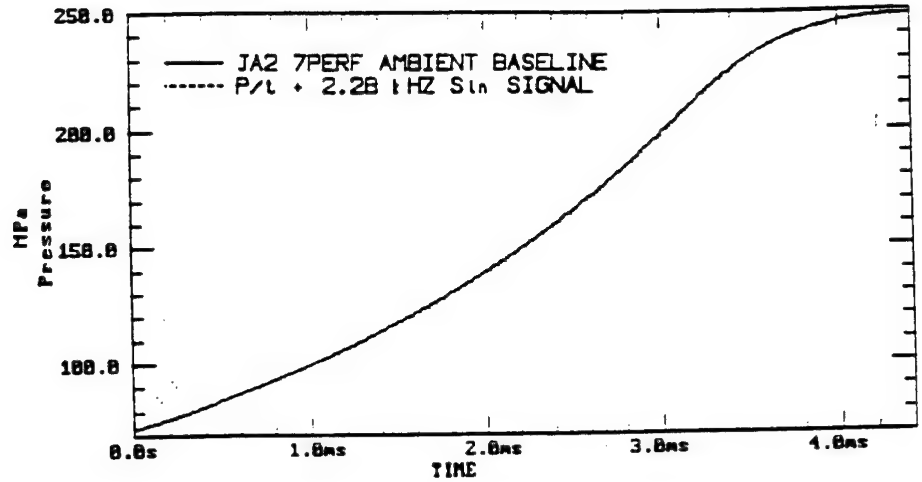

Figure 3a. P/t Signal and P/t Signal With Added Sin Signal at 2.28 kHz.

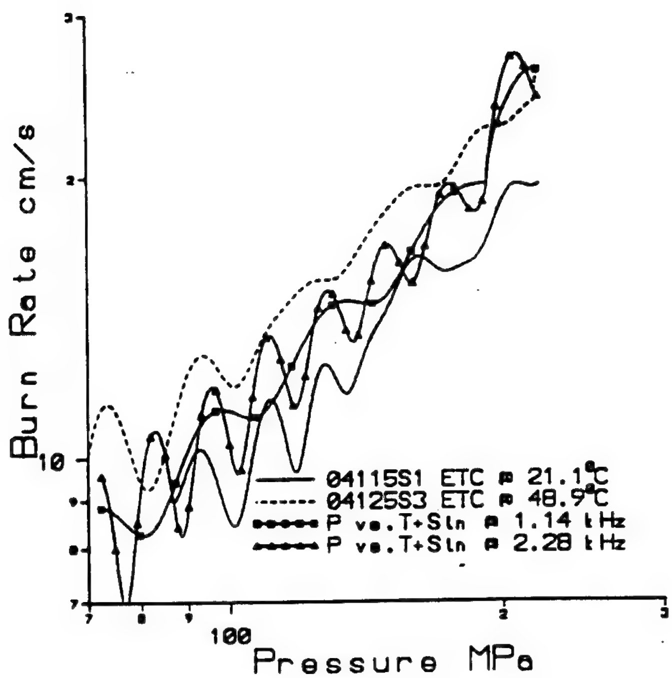

Figure 3b. Burn Rates of P/t Data With an Added Sin Signal at 1.14 kHz and 2.28 kHz vs. ETC at 21° and 49° C.

5. Impact of LPF

5.1 LPF Previous to BRLCB Burn-Rate Reduction. The simulated P/t data recorded alternatively with and without the fiber-optic link (case [a]) was smoothed with a LPF previous to the BRLCB burn-rate reduction, and no oscillations were observed, as shown in Figure 2. The parameters selected for this LPF were consistent for all data smoothing (a 2,500-Hz transition frequency, a 650-Hz transition width, and a maximum response of 0.01 outside the passband). Experimental (129.4 cm^3 closed chamber) non-ETC burn rates, obtained by low-pass-filtering the P/t data before their input into the BRLCB code, were also free from oscillations. For these non-ETC burn-rate reductions, as mentioned before, a visual comparison is possible between burn-rates independently of whether any smoothing is done or not. For these cases, the LPF smoothing process clearly did not introduce oscillations (Figures 4a and 4b). For ETC the effect of LPF previous to the BRLCB burn-rate reduction is shown in Figure 5b.

5.2 LPF After BRLCB Burn-Rate Reduction. For these non-ETC burn-rate reductions, the LPF smoothing done on the burn rates after the BRLCB code rendered the same effect as smoothing the initial data with the same LPF before the BRLCB code burn-rate deduction (Figure 4b). No oscillations were detected on these burn rates. The ETC burn rates deduced from initially nonsmoothed P/t data sets (Figure 5a) do not allow any comparison. However, ETC burn rates, deduced from initially LPF smoothed P/t data sets and ETC burn rates smoothed after being deduced, showed similar plots, but with oscillations (Figure 5b).

The same burn rates were also filtered with the BRLCB option 7 for non-ETC and ETC cases (Figures 4b and 5b) after selection of the cutoff frequencies from the FFT burn-rate amplitude spectrum (see Appendix D). This cutoff frequency selection was then used to generate the best smoothing effect on the burn rates. In general, for the signals considered, the amplitude spectrum (amplitude vs. frequency) plot showed the heaviest content at low-frequency values, and the effect of the smoothing reflected on the burn rate was acceptable and did not contribute to oscillations. On

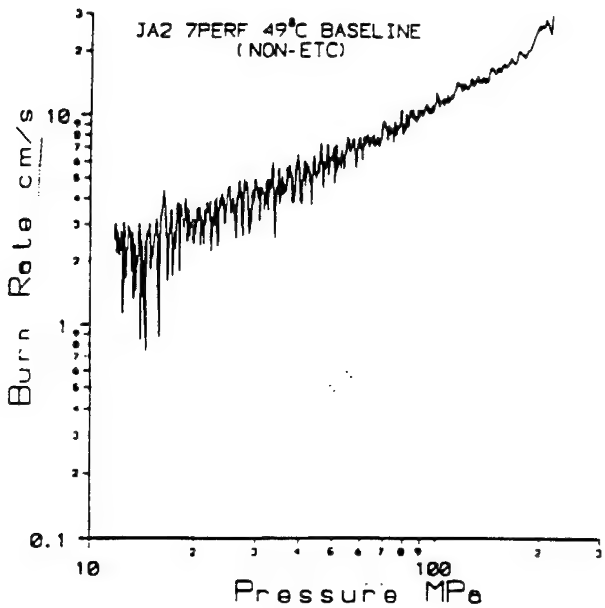

Figure 4a. Non-ETC Nonsmoothed Burn Rate (Ident 04275S9).

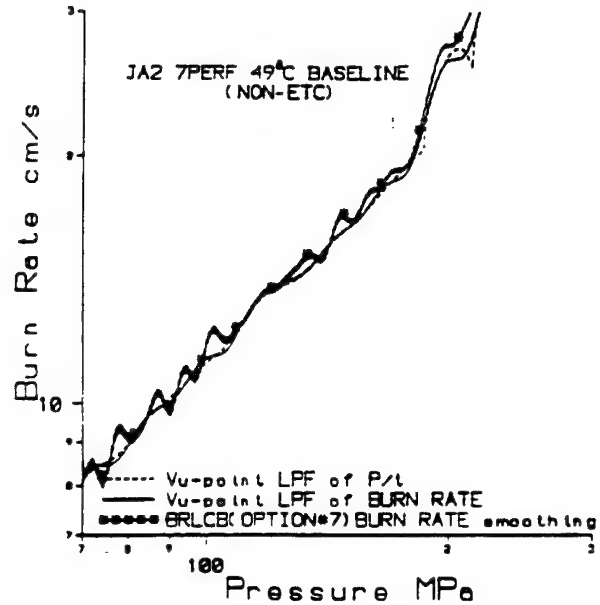

Figure 4b. Effects of Smoothing (Ident 04275S9).

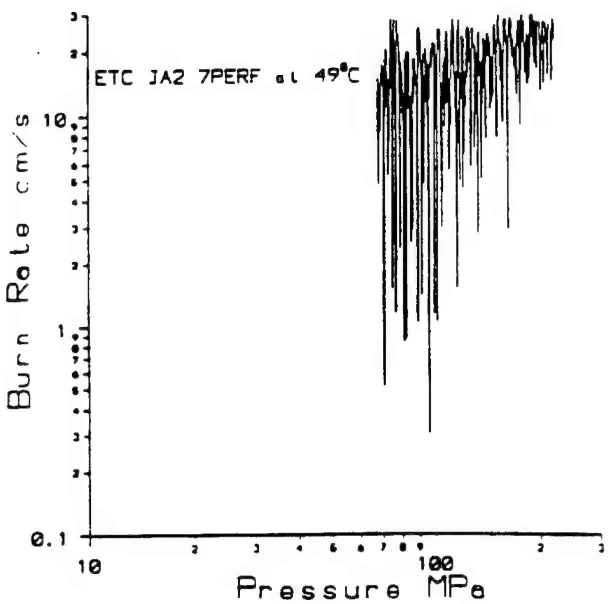

Figure 5a. ETC Nonsmoothed Burn Rate (Ident 04125S3).

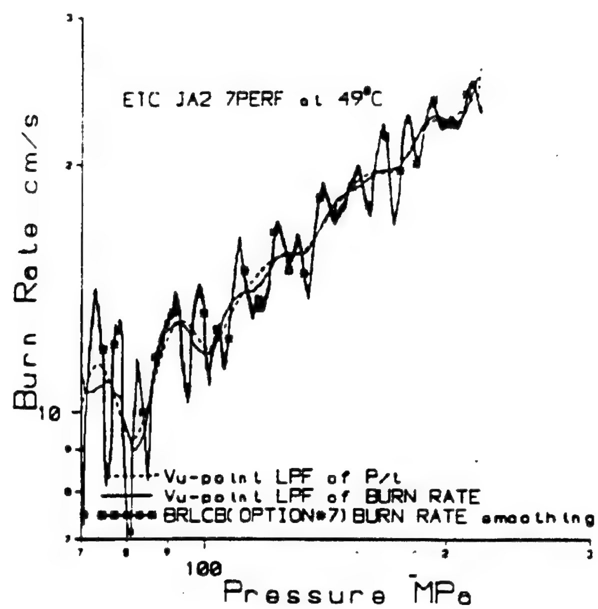

Figure 5b. Effects of Smoothing (Ident 04125S3).

the ETC 129.4-cm^3 closed-chamber reductions considered, the amplitude spectrum displayed typically had its highest frequency content for values of less than 0.1 Hz (Ident 4125S3, Appendix C). For the ETC cases, due to the large number of oscillations present to begin with, the filtered data usually retained many more of the undesired frequency components than for the non-ETC cases, and a more discriminating selection for the cutoff frequency should be used.

The Vu-point LPF smoothing of the initial P/t curve or of the deduced burn rates after the BRLCB reduction, allowed a larger passband and a narrower transition band, which eliminated higher frequencies more effectively than the application of the BRLCB option 7 (FFT). The Vu-point LPF smoothing used in these cases had a transition frequency of 2.5 kHz and a transition width of about 500 Hz. For non-ETC firings, the effects of the LPF filter before and after the burn-rate deduction by the BRLCB code, as well the BRLCB option 7 smoothing (FFT) of the burn rates, are shown in Figure 4b.

6. Energy Input Effect on a BRLCB ETC Burn-Rate Reduction

A BRLCB code ETC reduction differs from a non-ETC reduction as it requires the input of an "energy" file which describes the energy (MJ) vs. time corresponding to the event of the plasma injection. To determine the impact of this energy on a resulting burn-rate profile (case [d]), two cases were considered. First, a "synthetic" or oscillation-free P/t data file was coupled with an energy file and processed jointly in BRLCB as an ETC burn-rate reduction case. Second, P/t data from an experimental ETC firing was reduced in BRLCB without taking in account the input of the corresponding energy file.

Specifically, the two cases considered were (d-1) - a P/t file generated from an oscillation-free inverse analysis of an ambient non-ETC firing (JA2 7-perf baseline, Ident 04255S7), reduced as an ETC firing by including an energy file (04175S4.EGY) from a previous test (Figure 6a); and (d-2) - an ambient ETC P/t data file (Ident 04115S1) reduced as a non-ETC firing by not including its

energy input file (Figure 7a). Figure 6a shows case (d-1) with a lower burn rate, due to the added energy that decreases the amount of propellant to be burned by the code to match the same initial conditions (P/t curve). No oscillations were introduced by the addition of the energy file. This result was expected as the energy file and its derivative respect to time (Figure 6b) are also free from oscillations.

In case (d-2) a similar, yet higher than the previous one obtained, burn rate was expected with the energy file included, as the ETC P/t curve would force the code during the non-ETC reduction to increase the burn rate. However, Figure 7a shows a slighter lower burn rate (Ident 04115S1 NO-EGY FILE), which indicates that a higher heat-loss fraction than the code given 0.32889 (60% increase) should be assumed. In any case, the oscillations were retained for case (d-2) independently of the omission of the energy file during the code burn rate reduction.

ETC burn rates of JA2 disks at 16 kJ and 36 kJ (Idents 03154S1 and 04084S1) fired at ambient temperature, along with JA2 7-perf conditioned at 48.9° C and at 21 kJ (Ident 04175S4) are shown in Figure 7b. They all have oscillations independently of the propellant conditioning temperature and of the propellant grain geometry (i.e., disks or 7-perf cylindrical). These oscillations appear to taper off at about maximum pressure.

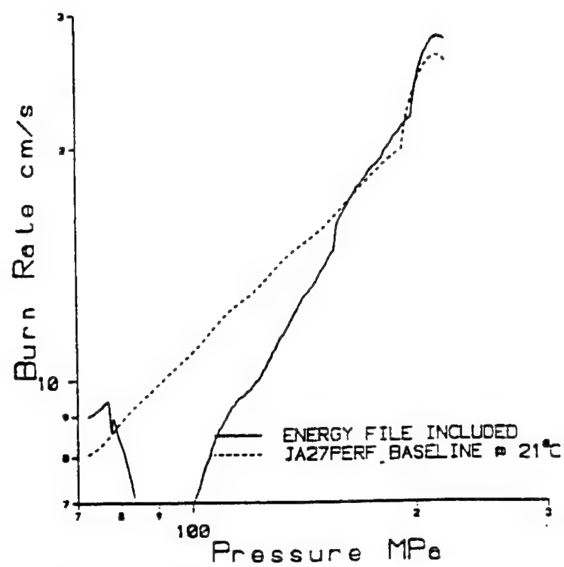

Figure 6a. Burn-Rate Plot of a Non-ETC File With Added (ETC) Energy File.

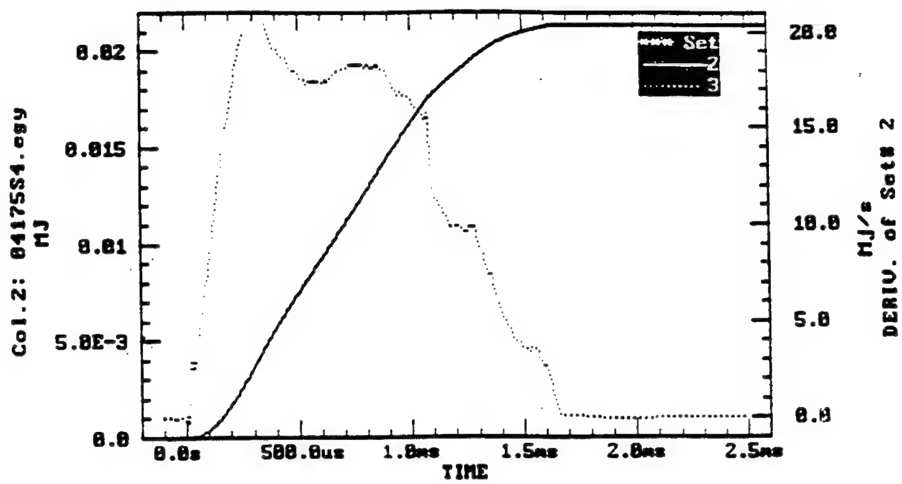

Figure 6b. PFN Energy (MJ) and Its Derivative Respect to Time.

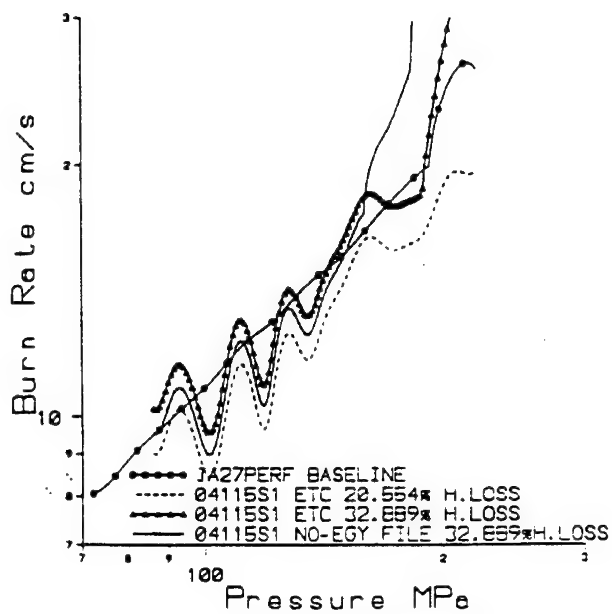

Figure 7a. ETC Burn-Rate Plot Deduced Without an Energy File Input.

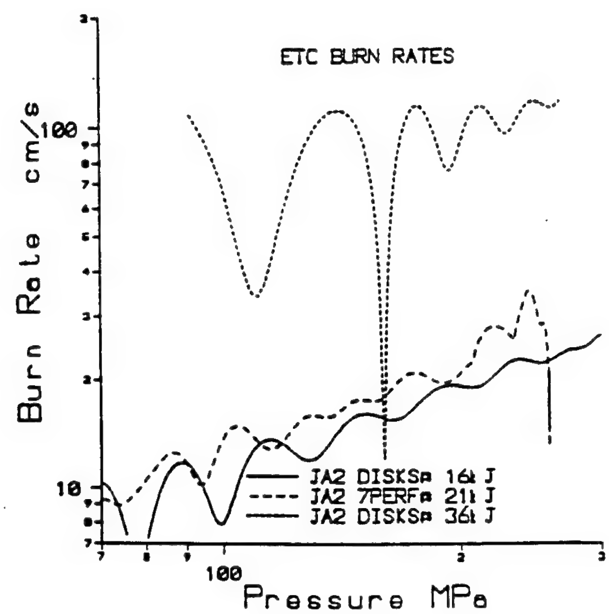

Figure 7b. ETC Burn Rates at 16 kJ, 21 kJ, and 36 kJ Average. (PFN Charged at 3 kV, 4 kV, and 5 kV, Respectively.)

7. Discussion

Generally, non-ETC deduced burn rates of firings conducted with the 129.4-cm^3 closed-chamber vessel seem to be free from oscillations. For these cases, a LPF on the initial P/t data before the burn-rate reduction, or a LPF on the deduced burn rate, produced very similar results. Both choices eliminated a substantial amount of noise from the initial P/t curve or from the final deduced burn rate respectively, allowing visual comparisons. For practical purposes, since the results are similar, the former method is the one of choice, as the smoothing of the final burn rates implies working with a large output file from which three columns (time per point, pressure, and burn rate) are extracted and imported into Vu-point where P/t and burn rate vs. time Log/Log plots determine the final plot of burn rate vs. pressure.

The burn rates, smoothed with the BRLCB option whose filter cutoff frequency is selected from inspection of the burn-rate FFT amplitude spectrum, generally provided a cutoff frequency value in the range of millihertz, limiting the smoothing effect. The Vu-point LPF smoothing allows a range of cutoff frequency values usually from hertz to kilohertz and a choice for the passband transition width.

It has been shown that the oscillations observed on ETC burn rates can be generated by the addition of a small-amplitude signal to a non-ETC P/t data set (Kooker, Appendix B). The burn rates for two 20-kJ firings were reproduced with the addition of small-amplitude signals to a P/t curve (1.14 kHz and 2.28 kHz), while the 16-kV firing (Indent 03154S1) was reproduced with a 2.0-kHz signal. It has also been shown that the addition of an energy file to a non-ETC burn-rate reduction or the omission of an energy file from an ETC burn-rate reduction was not related to the generation of oscillations.

The oscillations observed on the non-ETC burn rates deduced from the 200-cm^3 closed-chamber vessel were apparently caused by the improper selection of cutoff frequency values from the FFT amplitude spectrum.

For this discussion, so far, all of the ETC data considered were generated by the plasma ignition of a solid propellant in a 129.4-cm^3 closed-chamber vessel. It can also be pointed out that the oscillations are not dependent on the propellant grain geometry or on the propellant conditioning temperature, as data from different JA2 geometries (disks and 7-perf) were used (Figure 7b), as well as from different conditioning temperatures.

For ETC, however, the oscillations amplitude increases for plasmas of higher energy (Ident 04084S1, 36 kJ, Figure 7b). It is reasonable to speculate on what effect a higher chamber pressure gradient could have on the injected plasma and on the burn rates. This question becomes more relevant as burn rates from delayed plasma injection (Del Guercio, Stobie, and Oberle 1996b) are reviewed. These burn rates show oscillations at the low-pressure regime (up to 70 MPa), but a substantial decrease of them at higher pressure values (220 MPa). At low pressures, burn-rate oscillations are not uncommon, as they are known to be related to nonuniform ignition.

For the JA2 7-perf delayed plasma injection study, as the propellant is initially ignited conventionally (electric match ignition), and later on (10 ms later) the plasma injection takes place, the burn-rate analysis is split in two parts. A "burn-rate reduction," or conventional reduction, is done for the first part of the P/t data (Ident 09225S1) up to the moment of the plasma injection (Figure 8a). A second reduction or "ETC" reduction is done for the portion of the P/t data remaining up to maximum pressure (Figure 8a), which takes in account the electrical energy contributed by the plasma injection.

If the burn-rate reduction of the P/t data (Ident 09225S1) is carried over up to maximum pressure, ignoring the plasma energy input at 70 MPa, the transition from the initial type of oscillations, observed previous to the plasma injection to the ones present up to maximum pressure, can be clearly seen on Figure 8a. If this plot is compared against previous Figures 7a and 7b, the delayed plasma burn-rate profile clearly shows a different behavior. Curiously, the portion of the burn-rate plot, corresponding to the conventional ignition of the propellant previous to the plasma injection, shows more oscillations than a typical non-ETC combustion reduction. At this point, this matter is still

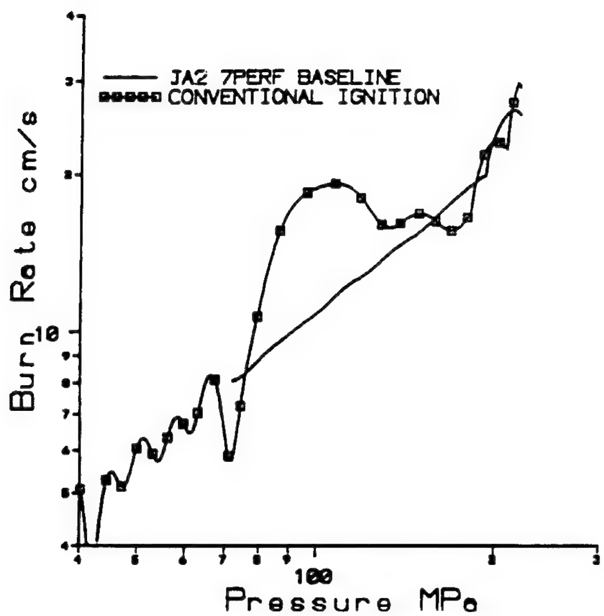

Figure 8a. Conventional Reduction of Delayed Plasma Injection (Ident 09225S1).

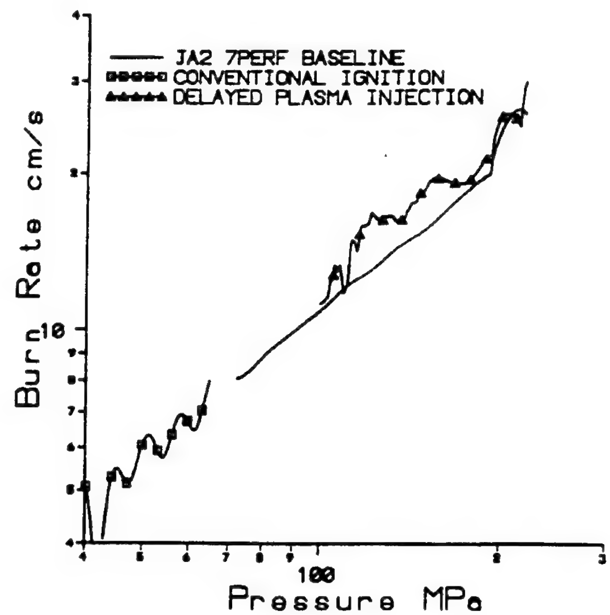

Figure 8b. Delayed Plasma Injection (Ident 09225S1) at 29.6 kJ.

unresolved; however, it is worth mentioning that there are differences in the setup for the electric match, whether it is used for a conventional (non-ETC) firing or for a delayed plasma injection firing, which may be contributing to this phenomena.

For a non-ETC firing, this match is placed inside the capillary tube (plasma injector) where it extrudes into the combustion chamber through the nozzle mouth. One of its leads is grounded, and the other lead is connected to the electrode tip (Del Guercio et al. 1995). For a delayed plasma injection, the capillary tube holds the exploding wire instead, and the match is located at the opposite end of the combustion chamber, extruding through a port commonly used to set the "muzzle" Kistler gauge and facing the opposite side of the propellant charge (Del Guercio, Stobie, and Oberle 1996b). Thus, the propellant is first conventionally ignited from the opposite side that is later impacted by the plasma injection.

8. Summary and Conclusions

The plasma injection event is then suspected to cause a disturbance on the chamber pressurization process, both for ETC and for delayed plasma injection cases. This seems to indicate that for ETC firings (1) oscillations are present on the burn-rate reductions, (2) oscillations are embedded on the P/t data, (3) the input of an energy file during the BRLCB code process does not add oscillations, (4) the plasma injection may influence the propellant combustion and chamber pressurization process, and (5) the amplitude of the oscillations observed is proportional to the energy of the plasma injected.

For delayed plasma injection firings, however, the oscillations previously observed for ETC firings from a 70-MPa to 220-MPa range appear to decrease as the plasma injection in this case occurs at higher chamber pressure values.

The rationale seems to be as follows: for ETC firings, the plasma enters a closed chamber, still nonpressurized by the propellant combustion, while for delayed plasma injection firings, the plasma wave enters a closed chamber, pressurized at about 70 MPa by the previous electric match ignition of the propellant.

Thus, it is logical to conclude that the closed-chamber plasma injection process contributes to burn-rate oscillations, that the oscillations amplitude is proportional to the plasma energy, and that these oscillations are dependent on the chamber pressure at the time of the plasma injection.

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Appendix A:

FORTRAN Code for Addition of Small-Amplitude Signal to P/t Curve

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```
c234567
c     SIGNAL.FOR/1996/Miguel Del Guercio
c     TEST PROG/TO READ INV.BR.DATAFILE(PT TRACE),AND ADD NOISE TO IT.
      real X , Y , L, A , B , C, D, E

      open (unit=1, file='INVBRS7.PVT', form = 'formatted'
     k, access='sequential', status='old')
      open (unit=2, file='dat.in',form ='formatted'
     k,access='sequential',status='new')

      PRINT*, 'SYNTHETIC PRESSURE/TIME MODIFICATION MENU'
      PRINT*, 'ENTER Vupoint window  length '
      PRINT*, ' '
      READ*,A
      PRINT*, 'ENTER data time per point '
      PRINT*, ' '
      READ*,B
      C = A/B
      NPOINTS = C
      write(6,600) C
600   format(5X,' the number of data points is : ',I8)
C     " select only integer part "
      DO 10  I = 1, NPOINTS
      READ (1, *, END=20) X,Y

      WRITE (2, 200)X,Y
200   FORMAT (2X,E12.6, 5X,E12.6)
20    CONTINUE
10    CONTINUE
      CLOSE (UNIT = 1)
      CLOSE (UNIT = 2)
99    L=0

      PRINT*, 'TO ADD A SINE WAVE ENTER 1'
      PRINT*, 'TO ADD A SINC FUNCTION ENTER 2'
      PRINT*, 'TO ADD RANDOM NOISE ENTER 3'
      PRINT*, 'TO EXIT THIS PROGRAM ENTER 4'
      PRINT*, ' '
      READ*, L
      IF (L .EQ. 1) THEN
      GOTO 91
      ELSEIF (L .EQ. 2) THEN
      GOTO 92
      ELSEIF (L .EQ. 3) THEN
      GOTO 93
      ELSEIF (L .EQ. 4) THEN
      GOTO 94

      ENDIF

91    call sinof
      PRINT*, 'THE OUTPUT FILE IS CALLED SINE.OUT'
      GOTO 99
92    call sinc
      PRINT*, ' THE OUTPUT FILE IS CALLED SINC.OUT'
      GOTO 99
93    call random
      PRINT*, ' THE OUTPUT FILE IS CALLED RANDOM.OUT'
      GOTO 99
94    STOP
      END

      subroutine sinof
      real x,y,pi,r,dr,s, C
      open (unit=2,file='dat.in',form='formatted'
     k,access='sequential',status='old')
      open (unit=3,file='sine.out',form='formatted'
     k,access='sequential',status='new')
      print*, ' enter number of data points'
```

```
      print*, ' '
      read*, C
      NPOINTS = C
      pi = 3.1415927
      dr =(pi)/(NPOINTS)

      do 30   I= 1,NPOINTS
       read (2, *, end = 40)x,y
      r = r + dr
      s = (pi/10) * (sin(10 * r))
      Y = y + s
      write (3, 300) X,Y
300   format(2X, E12.6,5X, E12.6)
40    continue
30    continue
      close (unit=2)
      close (unit=3)
      return
      end
      subroutine sinc
      real X,Y,u,du,v,D
      open (unit=2, file='dat.in',form='formatted'
     k, access='sequential', status='old')
      open (unit=4,file='sinc.out',form='formatted'
     k,access='sequential',status='new')
      print*, 'enter number of data points'
      print*, ' '
      read*, D
      npoints = D
      pi = 3.1415927
      du = pi/(npoints)
      u = pi/2

      do  50  I= 1,npoints
      read (2, *, end = 60) X,Y
      u = u + du
      v = (Sin(u)/(u))
      Y =  Y + v
      write (4,400)x,Y
400   format(2X, E12.6, 5X, E12.6)
60    continue
50    continue
      CLOSE (UNIT = 2)
      CLOSE (UNIT = 4)
      return
      end
      subroutine random
      real x,y,w,s,E
      open (unit=2, file='dat.in',form='formatted'
     k, access='sequential',status='old')
      open (unit=5, file='random.out',form='formatted'
     k, access='sequential',status='new')
      print*, ' enter number of data points'
      print*, ' '
      read*, E
      npoints = E
      pi = 3.1415927
      do  70  I = 1,npoints
      read (2, *,end = 80) X,Y
      w = pi * RANDS(Y/(X+1))
      Y = Y + w
      write (5, 500) X,Y
500   format(2X, E12.6,5X, E12.6)
80    CONTINUE
70    CONTINUE
      CLOSE (UNIT = 2)
      CLOSE (UNIT = 5)
      return
      end
```

Appendix B:

Comments on Solid Propellant Burn-Rate Oscillations

Note: This Appendix appears with no editorial change.

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25 July 1996

Some Comments on Solid Propellant Burn-Rate Oscillations

Douglas E. Kooker
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Propulsion and Flight Division/Propulsion Branch

Focus: Two recent U.S. Army Research Laboratory (ARL) Tech Notes report results[1, 2] from ETC closed-bomb tests of JA2 solid propellant (both slabs and 7-perf grains) in which the burn rates deduced with BRLCB exhibit large-amplitude low-frequency oscillations. These oscillations often persist up to pressures of 150–200 MPa, even though the plasma source expires after 1.5 ms (~ 8 ms cycle).

Concern: Is this behavior actually a burn-rate response of the solid propellant, or has it been influenced by other factors?

****

Even when the thermodynamics of the energetic material and the grain geometry have been determined, there are still two fundamental assumptions in the analysis underlying BRLCB:[3]

(1) the material is uniformly ignited at time t = 0, and

(2) there is no wave motion of any consequence within the chamber.

---

[1] Del Guercio M., I. Stobie, W. Oberle. "JA2 Electrothermal-Chemical (ETC) Firings With Modified 400-kJ Pulser." ARL-TN-66, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, May 1966.

[2] Del Guercio M., I. Stobie, W. Oberle. "Electrothermal-Chemical (ETC) Temperature Sensitivity of JA2 7-Perf Propellant." ARL-TN-67, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, June 1996a.

[3] Oberle, W., and D. Kooker. "BRLCB: A Closed-Chamber Data Analysis Program." ARL-TR-36, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, January 1993.

Of course, in practice, neither is completely satisfied. However, with these assumptions, wave motion in the chamber (whether from lack of uniform ignition or uneven distribution of burning material within the chamber) will necessarily lead to oscillations in the deduced burn rate. For this reason, closed-bomb burn rates at lower pressure (say below 20–30 MPa) are often discarded. There may also be some problems with slivering, etc., near burnout, which will also introduce error into the deduced burning at the highest pressures. However, the deduced rate is normally reliable over 20–80% of the pressure range.

The appearance of large-amplitude oscillations in burn rates over the entire pressure range is considered unusual behavior. Possibly some type of indepth combustion process could lead to such a result. Of course, "plasma-augmented burning" of solid propellant is still under investigation,[1, 2] but, if conversion of solid to gas occurs through regression of a "laminar" interface supported by a thermal wave in the solid, then it is not clear that a mechanism exists to drive large-amplitude oscillations in burn rate.

Of course, BRLCB will report burn-rate oscillations as the result of pressure waves in the combustion chamber. My feeling is that the usual solid propellant combustion process will not sustain large-amplitude pressure oscillations in a small chamber—without a major form of flow resistance (i.e., gas/solid drag within a compacted granular bed). There is a simple way to estimate the likely behavior of chamber oscillations on the deduced burn rate from a closed-bomb test—using the IB code XKTC.[4] I assumed the grain size and shape of the 7-perf JA2 propellant grains studied in Del Guercio, Stobie, and Oberle.[2] These grains are "burned" at 0.216 g/cm^3 loading density in a 129.4-cm^3 closed chamber with the same dimensions as the electrothermal chemical (ETC) closed-bomb. The pressure-time (P/t) curve generated by XKTC is shown by the solid line in Figure B-1;

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[1] Del Guercio M., I. Stobie, W. Oberle. "JA2 Electrothermal-Chemical (ETC) Firings With Modified 400-kJ Pulser." ARL-TN-66, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, May 1966.

[2] Del Guercio M., I. Stobie, W. Oberle. "Electrothermal-Chemical (ETC) Temperature Sensitivity of JA2 7-Perf Propellant." ARL-TN-67, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, June 1996a.

[4] Gough, P. S. "The Nova Code: A User's Manual." IHCR-80-8, Naval Ordnance Station, Indian Head, MD, December 1980.

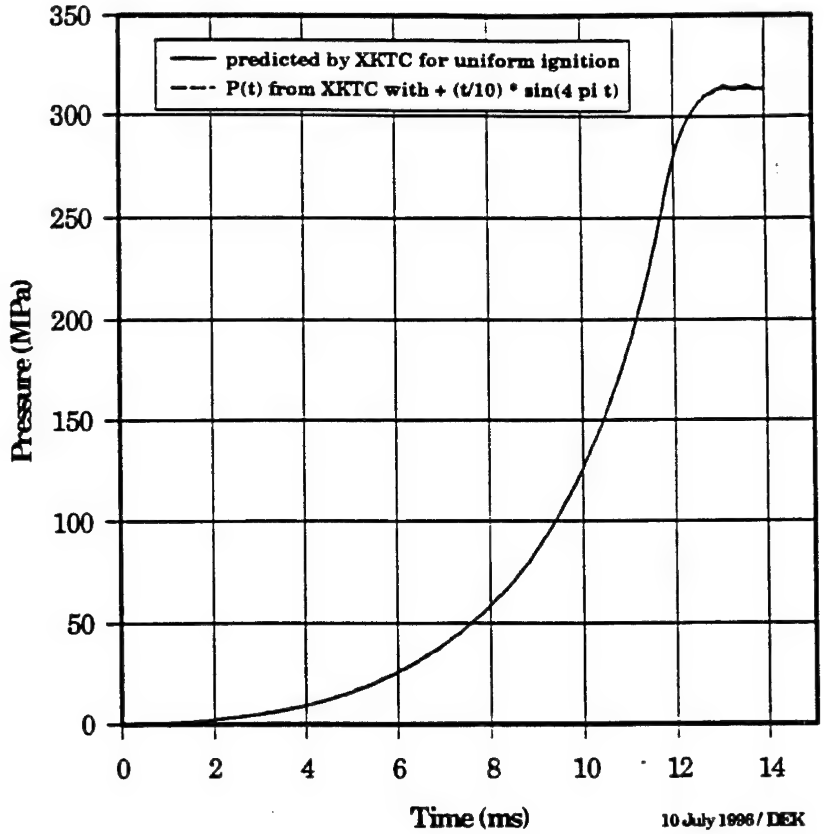

Figure B-1. P/t History From XKTC Simulation (Solid Curve) of Combustion of 7-Perf JA2 Solid Propellant (L = 0.602 in, D = 0.30 in, d = 0.026 in) at Loading Density of 0.216 g/cm³ Uniformly Ignited in 129.4 cm³ ETC Closed Bomb. Dashed Line Is Artificial Curve Formed by Addition of Small-Amplitude Oscillation ([t/10]*sin [4 pi t]) to Solid Curve.

this curve can then be fed into BRLCB to deduce the propellant burn rate, which can be compared to the original rate used in XKTC.

I tried a number of different combinations of propellant distribution and ignition mode (uniformly ignited, strong end-ignition, etc.). As expected, chamber oscillations show up as burn-rate oscillations; but the chamber oscillations created by nonuniform ignition and propellant distribution all die away above 30 MPa, and, hence, the oscillations in burning rate do also. An example computation is shown in Figure B-2. Based on fluid mechanics, sustaining chamber oscillations in a 129.4 cm^3 volume at high pressures is quite difficult.

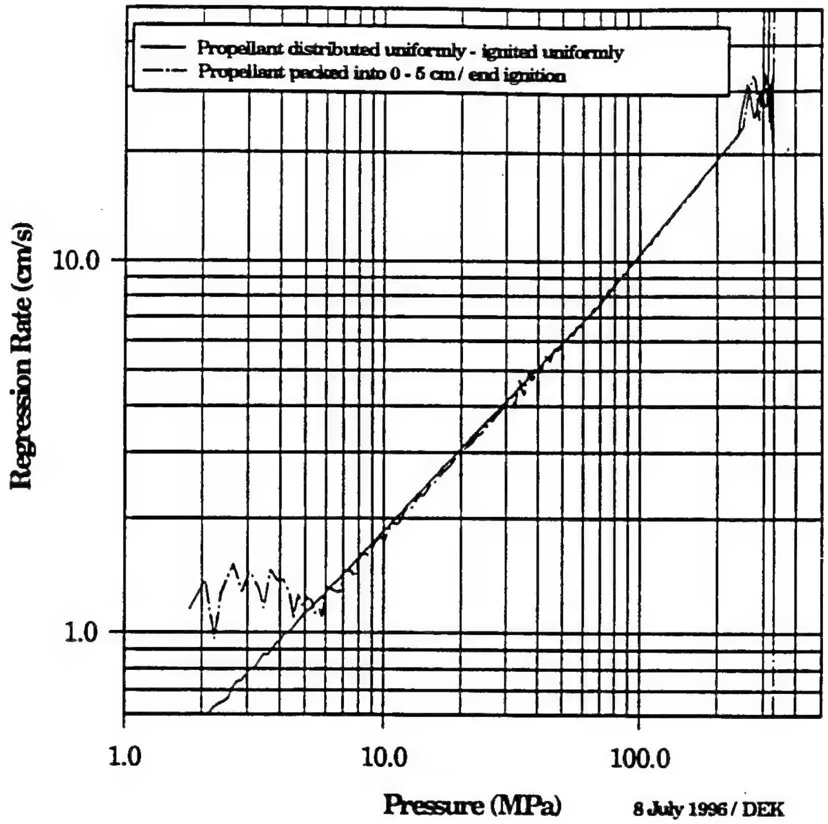

Figure B-2. Regression Rate for Granular JA2 Propellant Deduced by BRLCB as a Function of Pressure. Assumes 129.4 cm^3 ETC Closed Chamber. Solid Line Follows From Smooth P/t Curve Illustrated in Figure B-1, Which Assumes Uniform Ignition. Chain-Dot Line Is Similar Calculation When Same Propellant Is Packed Into First 5 cm of Chamber and Ignited at That End—Essentially Disturbances Die Away Above 20 MPa.

An entirely separate worry might be the possibility of an extraneous signal superposed on the P/t curve. I played with a few examples, where a small-amplitude "signal" (of the form t * sin [w*t]) was deliberately added to the otherwise smooth P/t curve generated by uniform ignition of the JA2 propellant grains spread uniformly through the chamber (solid line in Figure B-1). When the composite P/t curve is plotted (dashed line in Figure B-1), the curve still appears smooth, but with small-amplitude noise. However, the burn rate deduced by BRLCB from this composite curve is characterized by large-amplitude oscillations all the way to 200 MPa—similar to the data in Del

Guercio, Stobie, and Oberle.[1, 2] This result is shown dramatically in Figure B-3, and in more detail for the restricted range of pressure in Figure B-4. Of course, this example is not proof, but it suggests a possibility.

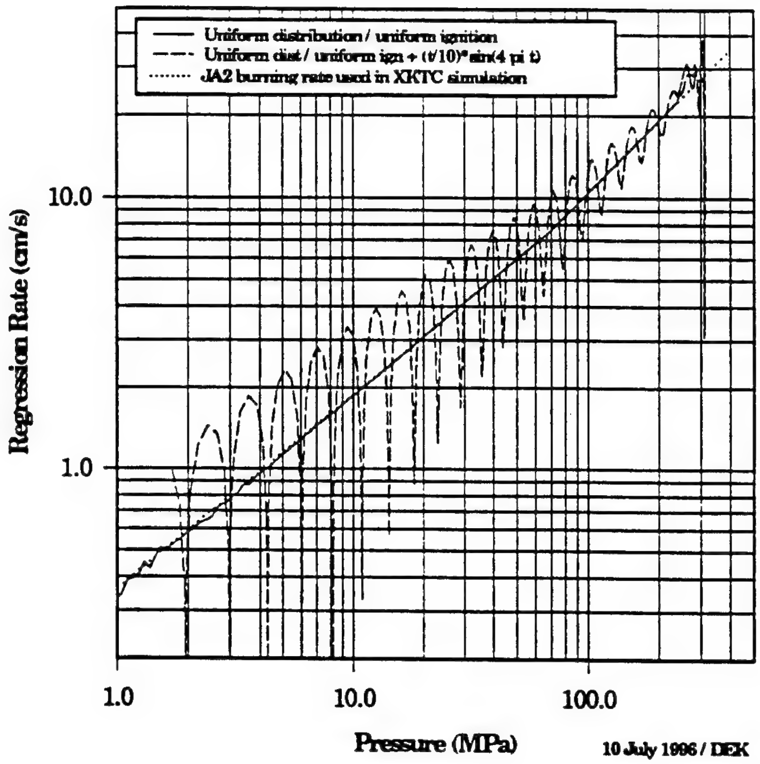

Figure B-3. Regression Rate for Granular JA2 Propellant Deduced by BRLCB as a Function of Pressure (Small-Amplitude Pressure Disturbance Added). Assumes 129.4 cm^3 ETC Closed Chamber. Dashed Line Is Result Predicted by BRLCB Based on P/t Curve With Small-Amplitude Pressure Disturbance (Dashed Line in Figure B-1). Solid Line Follows From Smooth P/t Curve (Solid Line in Figure B-1), Which Assumes Uniform Ignition. Dotted Line Is Burn Rate Assumed in XKTC Simulation.

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[1] Del Guercio M., I. Stobie, W. Oberle. "JA2 Electrothermal-Chemical (ETC) Firings With Modified 400-kJ Pulser." ARL-TN-66, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, May 1966.

[2] Del Guercio M., I. Stobie, W. Oberle. "Electrothermal-Chemical (ETC) Temperature Sensitivity of JA2 7-Perf Propellant." ARL-TN-67, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, June 1996a.

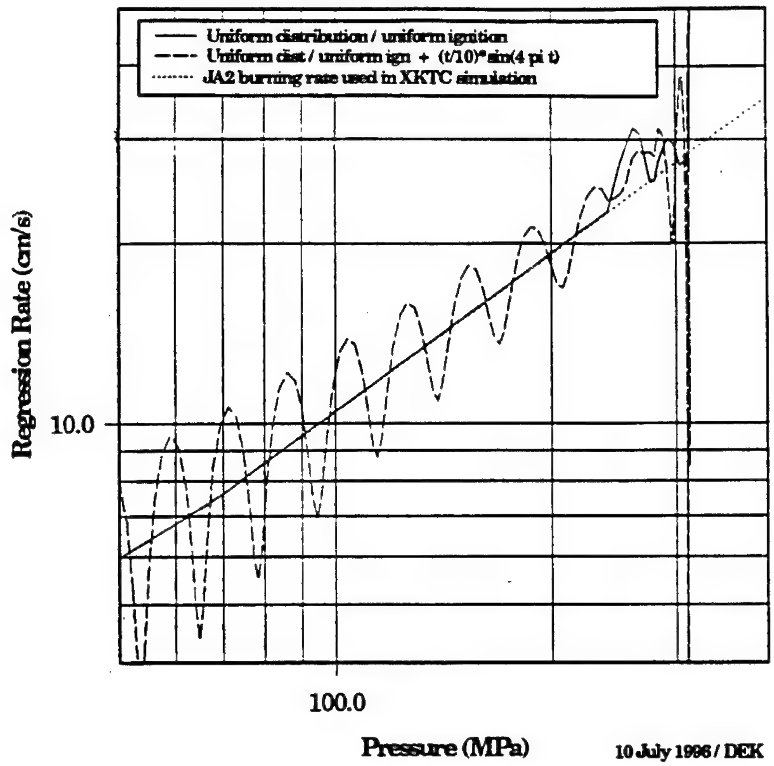

Figure B-4. Same Result Shown in Figure B-3, But in Restricted Pressure Range. Regression Rate for Granular JA2 Propellant Deduced by BRLCB as a Function of Pressure. Assumes 129.4 cm³ ETC Closed Chamber. Dashed Line Is Result Predicted by BRLCB, Based on P/t Curve With Small-Amplitude Pressure Disturbance (Dashed Line in Figure B- 1). Solid Line Follows From Smooth P/t Curve (Solid Line in Figure B-1), Which Assumes Uniform Ignition. Dotted Line Is Burn Rate Assumed in XKTC Simulation.

Appendix C:

BRLCB Burn-Rate Reductions

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BURNING RATE ANALYSIS
BRLCB V3.0
ADVANCED BALLISTIC CONCEPTS BRANCH - BRL

```
Project : ja2                    Requested by            : guercio
Inf File: F12WW.inf              Created From .MAS File : ja2.mas
P/T File: F12WW.pvt              Calculation Output File: F12WW.out
Smoothed: F12WW.pdt              Graphics File           : F12WW.dat
Fired on:
FIRING REMARKS:
P/t curve from Sin wave. LPF, with charge-amp, with f.o.Disk ID"ETC 8A1",
track #12.
REDUCTIONS REMARKS:
Used JA2.MAS as JA2 matched raise time of 3.5ms of Sin wave Pmax.
                    IGNITER INFORMATION
The Igntier Used Is          : Black Powder        Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

     IGNITER THERMOCHEMICAL PROPERTIES:
Impetus (J/g)        :    290.0 Molecular Weight  :  66.37000
Flame Temperature (K):   2188.0 Covolume (cc/g)   :    .78500
Density (g/cc)       :  1.75000 Gamma             :   1.21840

                   PROPELLANT INFORMATION
The Propellant Used Is          :                   Lot:
The Source For The Propellant Is:

 Propellant Thermochemical Properties: Following
 Sheets of Output

                   PROPELLANT GRAIN GEOMETRY

Grain Type:1-Perf. Cyl.
          Length --- (cm.):   .139700
          Outer Diam.(cm.):  2.882900
          Perf Diam. (cm.):  1.270000
          Inner Web  (cm.):   .806450

     Bomb Information              Gage Information
---------------------------------------------------
Bomb Type    :Closed Chamber       Gage I.D.     : None
Bomb Vol (cc):      129.4          Input Voltage:   .0000
                                   Constants For Fit: A+Bx+C^2
                                   A:    .00000E+00
                                   B:    .00000E+00
                                   C:    .00000E+00

        Temperature and Charge Mass Information
---------------------------------------------------
Propellant Mass (g)   :  30.0000      Igniter Mass (g):    .5000
Initial Temp. Prop.(K):  294.         Igniter Temp.(K):  294.
Initial Bomb Temp. (K):  294.
Number of Propellant Grains:    25.52


Number of Wildpoint Passes:   1 Wildpoint Tolerance:  5.000
Number of Smoothing Passes:   1 Smoothing Option:  1
Bridge Length: 15
1 OUTPUT FILE: F12WW.OP7
 ****************************************************************************************

 ****************************************************************************************

     Total # Layers =    1

     Chamber Volume (cm3) =   129.400

     Heat-Loss-Fraction (n-d) =      .000

     Time Step (mil-sec) =   .20000000E-02     Max Time Steps =    1200
```

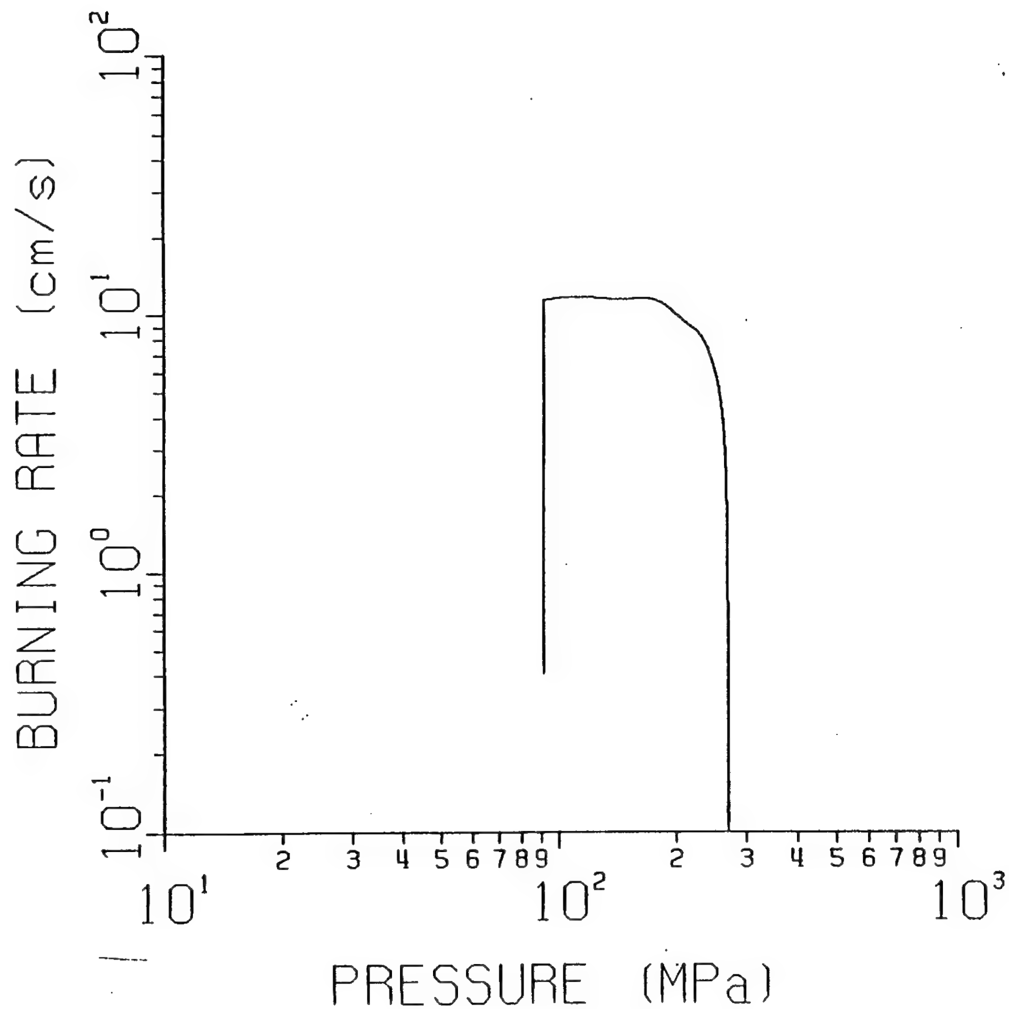

Figure C-1. Burn-Rate Plot F12WW.out.

```
                    BURNING RATE ANALYSIS
                        BRLCB V3.0
          ADVANCED BALLISTIC CONCEPTS BRANCH - BRL


Project : ja2                  Requested by          : guercio
Inf File: F13NW.inf            Created From .MAS File : ja2.mas
P/T File: F13NW.pvt            Calculation Output File: F13NW.out
Smoothed: F13NW.pdt            Graphics File          : F13NW.dat
Fired on:
FIRING REMARKS: P/t curve from Sine wave. LPF, without charge-amp, with f.o.
Disk "ETC 8A1", track #13.
REDUCTION REMARKS:Used JA2.Mas, as JA2 matched raise time to Pmax of Sin wave.
Assume loading density according to Blake code.
                  IGNITER INFORMATION
The Igntier Used Is          : Black Powder          Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

     IGNITER THERMOCHEMICAL PROPERTIES:
Impetus (J/g)         :      290.0 Molecular Weight  :  66.37000
Flame Temperature (K):      2188.0 Covolume (cc/g)   :    .78500
Density (g/cc)        :    1.75000 Gamma             :   1.21840

                  PROPELLANT INFORMATION
The Propellant Used Is           :                     Lot:
The Source For The Propellant Is:

 Propellant Thermochemical Properties: Following
 Sheets of Output

                  PROPELLANT GRAIN GEOMETRY

Grain Type:1-Perf. Cyl.
          Length --- (cm.):   .139700
          Outer Diam.(cm.):  2.882900
          Perf Diam. (cm.):  1.270000
          Inner Web  (cm.):   .806450

     Bomb Information                Gage Information
-------------------------------------------------------
Bomb Type     :Closed Chamber        Gage I.D.     : None
Bomb Vol (cc):      129.4            Input Voltage:    .0000
                                     Constants For Fit: A+Bx+C^2
                                     A:     .00000E+00
                                     B:     .00000E+00
                                     C:     .00000E+00

        Temperature and Charge Mass Information
-------------------------------------------------------
Propellant Mass (g)    :  30.0000     Igniter Mass (g):     .5000
Initial Temp. Prop.(K):  294.         Igniter Temp.(K):  294.
Initial Bomb Temp. (K):  294.
Number of Propellant Grains:    25.52


Number of Wildpoint Passes:   1 Wildpoint Tolerance:  5.000
Number of Smoothing Passes:   1 Smoothing Option:  1
Bridge Length: 15
1 OUTPUT FILE: F13NW.OP7
 ***********************************************************************************

 ***********************************************************************************

     Total # Layers =    1

     Chamber Volume (cm3) =   129.400

     Heat-Loss-Fraction (n-d) =       .000

     Time Step (mil-sec) =   .20000000E-02    Max Time Steps =     1200
```

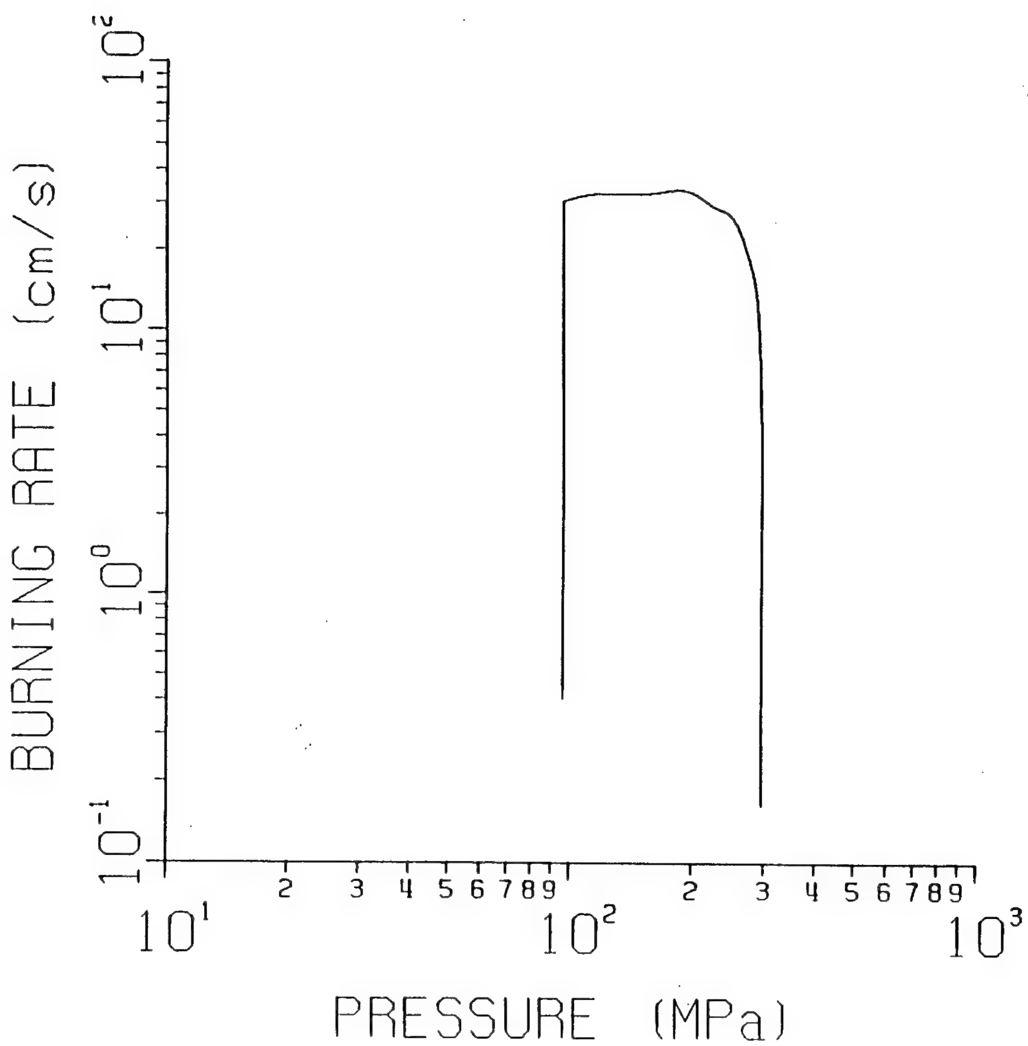

Figure C-2. Burn-Rate Plot F13NW.out.

```
                        BURNING RATE ANALYSIS
                             BRLCB V3.0
              ADVANCED BALLISTIC CONCEPTS BRANCH - BRL


Project : ja2                   Requested by          : guercio
Inf File: F14NN.inf             Created From .MAS File : ja2.mas
P/T File: F14NN.pvt             Calculation Output File: F14NN.out
Smoothed: F14NN.pdt             Graphics File          : F14NN.dat
Fired on:
FIRING REMARKS:P/t curve from Sin wave.LPF, without charge-amp, without f.o.
Disk ID "ETC 8A1", track #13.
REDUCTIONS REMARKS:Used JA2.MAS as JA2 matched raise time of 3.5ms of Sin wave Pmax.

                     IGNITER INFORMATION
The Igntier Used Is          : Black Powder          Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

     IGNITER THERMOCHEMICAL PROPERTIES:
Impetus (J/g)          :     290.0 Molecular Weight  :  66.37000
Flame Temperature (K):    2188.0 Covolume (cc/g)    :    .78500
Density (g/cc)         :   1.75000 Gamma              :   1.21840

                     PROPELLANT INFORMATION
The Propellant Used Is             :                       Lot:
The Source For The Propellant Is:

 Propellant Thermochemical Properties: Following
 Sheets of Output

                     PROPELLANT GRAIN GEOMETRY

Grain Type:1-Perf. Cyl.
          Length --- (cm.):    .139700
          Outer Diam.(cm.):   2.882900
          Perf Diam. (cm.):   1.270000
          Inner Web  (cm.):    .806450

     Bomb Information               Gage Information
--------------------------------------------------
Bomb Type     :Closed Chamber       Gage I.D.     : None
Bomb Vol (cc):       129.4          Input Voltage:    .0000
                                    Constants For Fit: A+Bx+C^2
                                    A:    .00000E+00
                                    B:    .00000E+00
                                    C:    .00000E+00

        Temperature and Charge Mass Information
--------------------------------------------------
Propellant Mass (g)    :  30.0000      Igniter Mass (g):     .5000
Initial Temp. Prop.(K):  294.          Igniter Temp.(K):  294.
Initial Bomb Temp. (K):  294.
Number of Propellant Grains:     25.52


Number of Wildpoint Passes:    1 Wildpoint Tolerance:  5.000
Number of Smoothing Passes:    1 Smoothing Option:  1
Bridge Length: 15
1 OUTPUT FILE: F14NN.OP7
 ***************************************************************************************

 ***************************************************************************************

     Total # Layers =     1

     Chamber Volume (cm3) =    129.400

     Heat-Loss-Fraction (n-d) =       .000

     Time Step (mil-sec) =    .20000000E-02     Max Time Steps =     1200
```

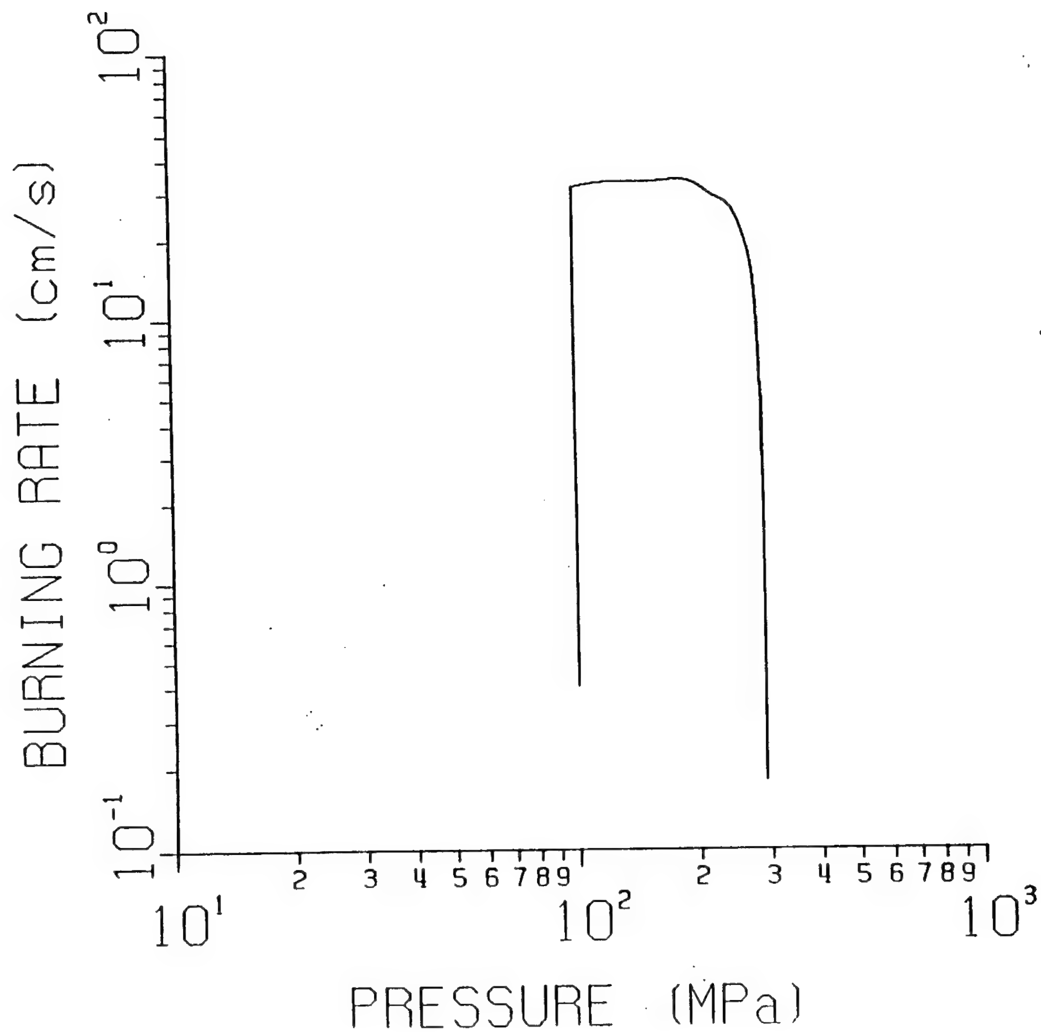

Figure C-3. Burn-Rate Plot F14NN.out.

ETC BURN RATE ANALYSIS
BRLCB V3.0
ADVANCED BALLISTIC CONCEPTS BRANCH - BRL

```
Project : 120CC CLOSED BOMB     Requested by            : DEL GUERCIO
Inf File: INVETC.inf            Created From .MAS File : JA27PERF.MAS
P/T File: INVETC.pvt            Calculation Output File: INVETC.out
Smoothed: INVETC.pdt            Graphics File           : INVETC.dat
EE  File: B:04175S4.EGY
Fired on:
FIRING REMARKS:
INVBRS7.PVT FILE REDUCED AS ETC FIRING USING 04175S4.EGY FILE
TO DETERMINE PRESENCE OF OSCILLATIONS ON THE REDUCED BR
COMPARED TO 04255S7 CONVENTIONAL.

                    IGNITER INFORMATION
The Igntier Used Is          : Black Powder        Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

     IGNITER THERMOCHEMICAL PROPERTIES:
Impetus (J/g)        :     290.0 Molecular Weight  :  66.37000
Flame Temperature (K):    2188.0 Covolume (cc/g)   :    .78500
Density (g/cc)       :   1.75000 Gamma             :   1.21840

                    PROPELLANT INFORMATION
The Propellant Used Is          : JA-2 7-PERF GRANULAR Lot: RAD-PE-792-71
The Source For The Propellant Is: RADFORD ARMY AMMUNIT

 Propellant Thermochemical Properties: Following
 Sheets of Output

                    PROPELLANT GRAIN GEOMETRY

Grain Type:7-Perf. Cyl.
          Length --- (cm.):  1.529080
          Outer Diam.(cm.):   .762000
          Perf Diam. (cm.):   .066040
          Inner Web  (cm.):   .130810
          Outer Web  (cm.):   .151130

     Bomb Information                 Gage Information
---------------------------------------------------
Bomb Type     :Closed Chamber         Gage I.D.     : None
Bomb Vol (cc):      129.4             Input Voltage:    .0000
                                      Constants For Fit: A+Bx+C^2
                                      A:    .00000E+00
                                      B:    .00000E+00
                                      C:    .00000E+00

        Temperature and Charge Mass Information
---------------------------------------------------
Propellant Mass (g)   :  27.1820      Igniter Mass (g):    .0000
Initial Temp. Prop.(K):  294.         Igniter Temp.(K):  294.
Initial Bomb Temp. (K):  294.
Number of Propellant Grains:    25.72

Number of Wildpoint Passes:   1 Wildpoint Tolerance:  5.000
Number of Smoothing Passes:   1 Smoothing Option:  1
Bridge Length: 15
1 OUTPUT FILE: INVETC.OP7
 ********************************************************************************

 ********************************************************************************

     Total # Layers =     1

     Chamber Volume (cm3) =   129.400

     Heat-Loss-Fraction (n-d) =       .000
```

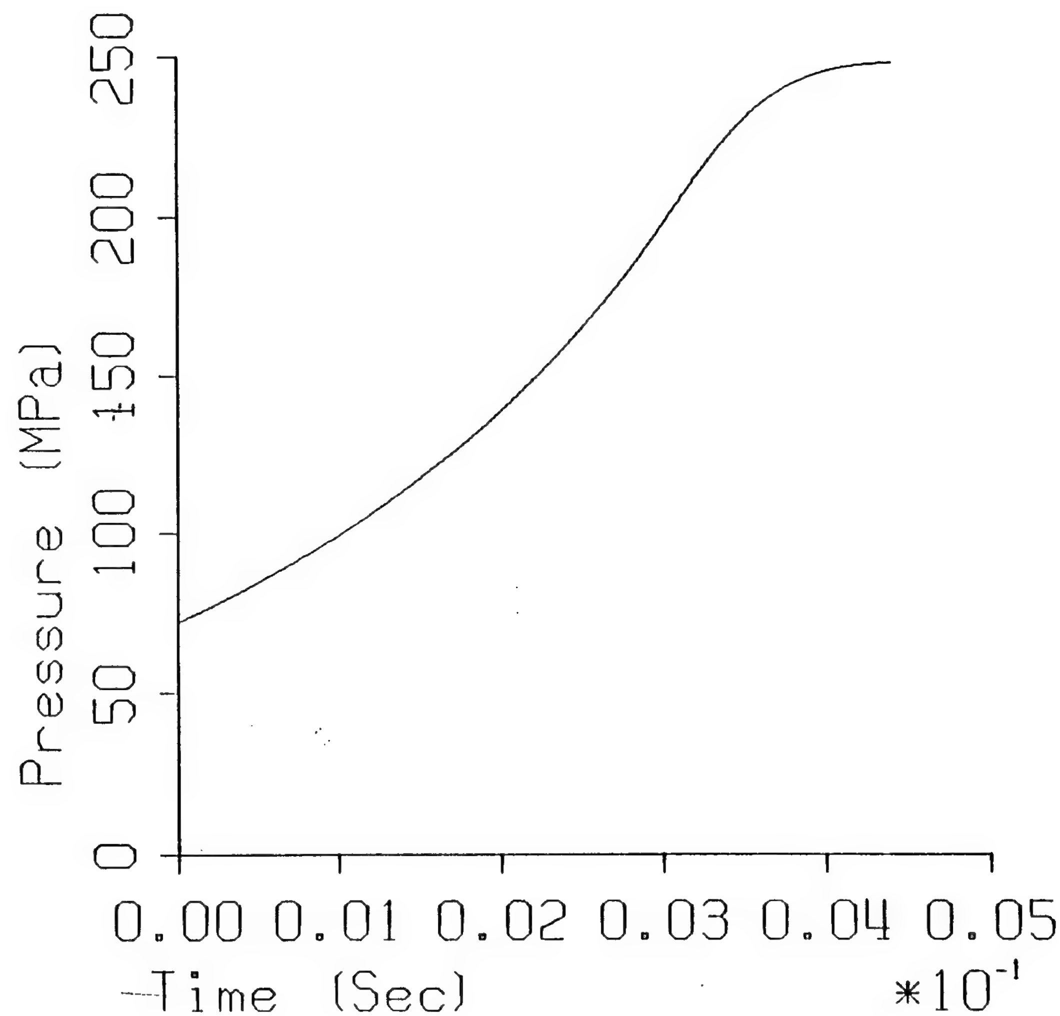

Figure C-4. P/t File INVETC.pvt.

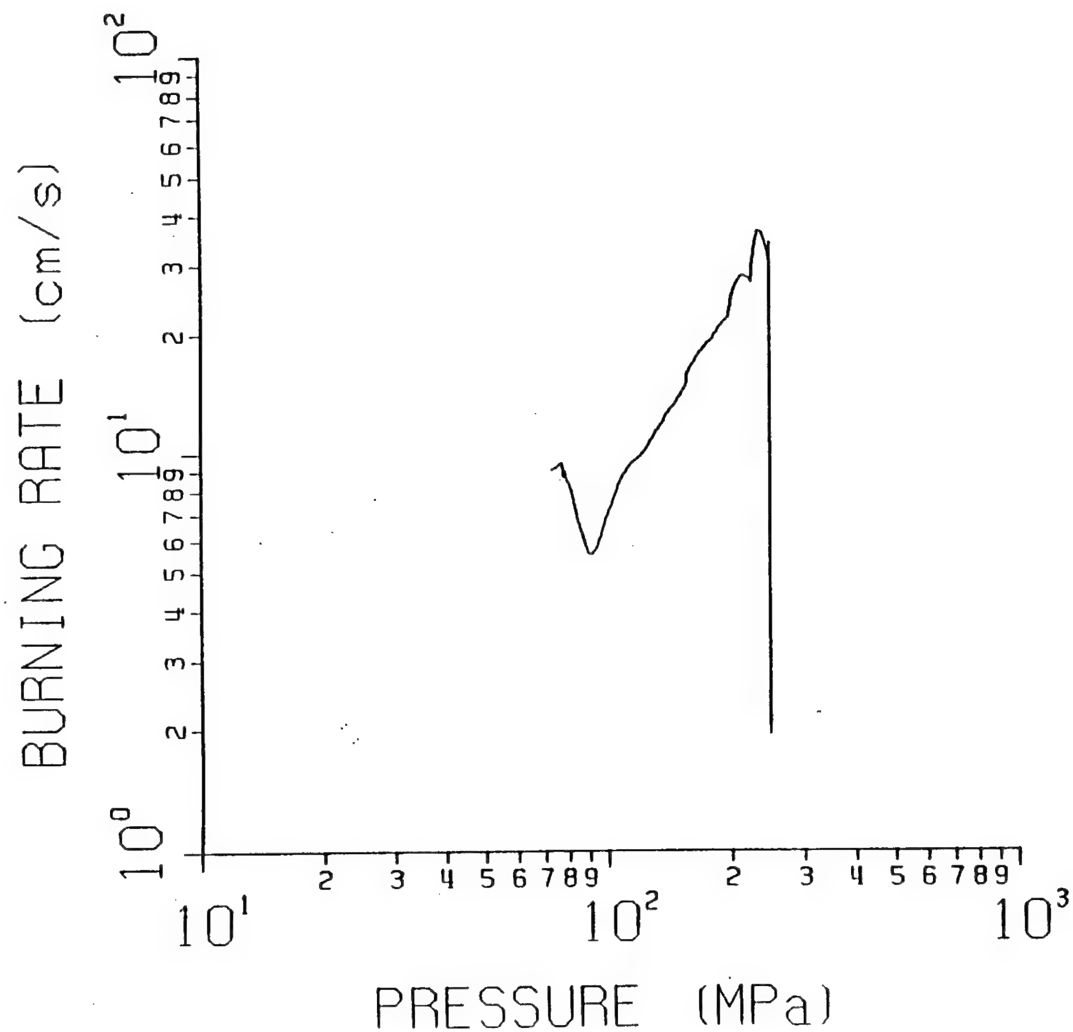

Figure C-5. Burn-Rate Plot INVETC.out.

BURNING RATE ANALYSIS
BRLCB V3.0
ADVANCED BALLISTIC CONCEPTS BRANCH - BRL

```
Project : 120CC CLOSED BOMB     Requested by           : DEL GUERCIO
Inf File: SINEOUT.inf           Created From .MAS File : JA27PERF.MAS
P/T File: SINEOUT.pvt           Calculation Output File: SINEOUT.out
Smoothed: SINEOUT.pdt           Graphics File          : SINEOUT.dat
Fired on:
FIRING REMARKS:
BR CALCULATED WITH "INVBRS7.PVT ORIGINATED FROM 04255S7
WHICH IS THE JA27PERF BASELINE AT 21.1 C
REDUCTION REMARKS:
SINE WAVE SIGNAL ADDED TO "PT" CURVE BY "SIGNAL.FOR" WITH 1.14 kHz FCY.
ITS OUTPUT IS "SINEOUT.OUT" RENAMED:B:SINEOUT.AD

                    IGNITER INFORMATION
The Igntier Used Is          : Black Powder        Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

     IGNITER THERMOCHEMICAL PROPERTIES:
Impetus (J/g)          :    290.0 Molecular Weight  :  66.37000
Flame Temperature (K):     2188.0 Covolume (cc/g)   :    .78500
Density (g/cc)       :    1.75000 Gamma             :   1.21840

                    PROPELLANT INFORMATION
The Propellant Used Is         : JA-2 7-PERF GRANULAR Lot: RAD-PE-792-71
The Source For The Propellant Is: RADFORD ARMY AMMUNIT

 Propellant Thermochemical Properties: Following
 Sheets of Output

                    PROPELLANT GRAIN GEOMETRY

Grain Type:7-Perf. Cyl.
          Length --- (cm.):  1.529080
          Outer Diam.(cm.):   .762000
          Perf Diam. (cm.):   .066040
          Inner Web  (cm.):   .130810
          Outer Web  (cm.):   .151130

     Bomb Information               Gage Information
-------------------------------------------------
Bomb Type    :Closed Chamber        Gage I.D.    : None
Bomb Vol (cc):      129.4           Input Voltage:    .0000
                                    Constants For Fit: A+Bx+C^2
                                    A:   .00000E+00
                                    B:   .00000E+00
                                    C:   .00000E+00

        Temperature and Charge Mass Information
-------------------------------------------------
Propellant Mass (g)    :  27.1820      Igniter Mass (g):    .5750
Initial Temp. Prop.(K):  294.          Igniter Temp.(K):  294.
Initial Bomb Temp. (K):  294.
Number of Propellant Grains:    25.72


Number of Wildpoint Passes:   1 Wildpoint Tolerance:  5.000
Number of Smoothing Passes:   1 Smoothing Option:  1
Bridge Length: 15
1 OUTPUT FILE: SINEOUT.OP7
*****************************************************************************************

*****************************************************************************************

    Total # Layers =    1

    Chamber Volume (cm3) =   129.400
```

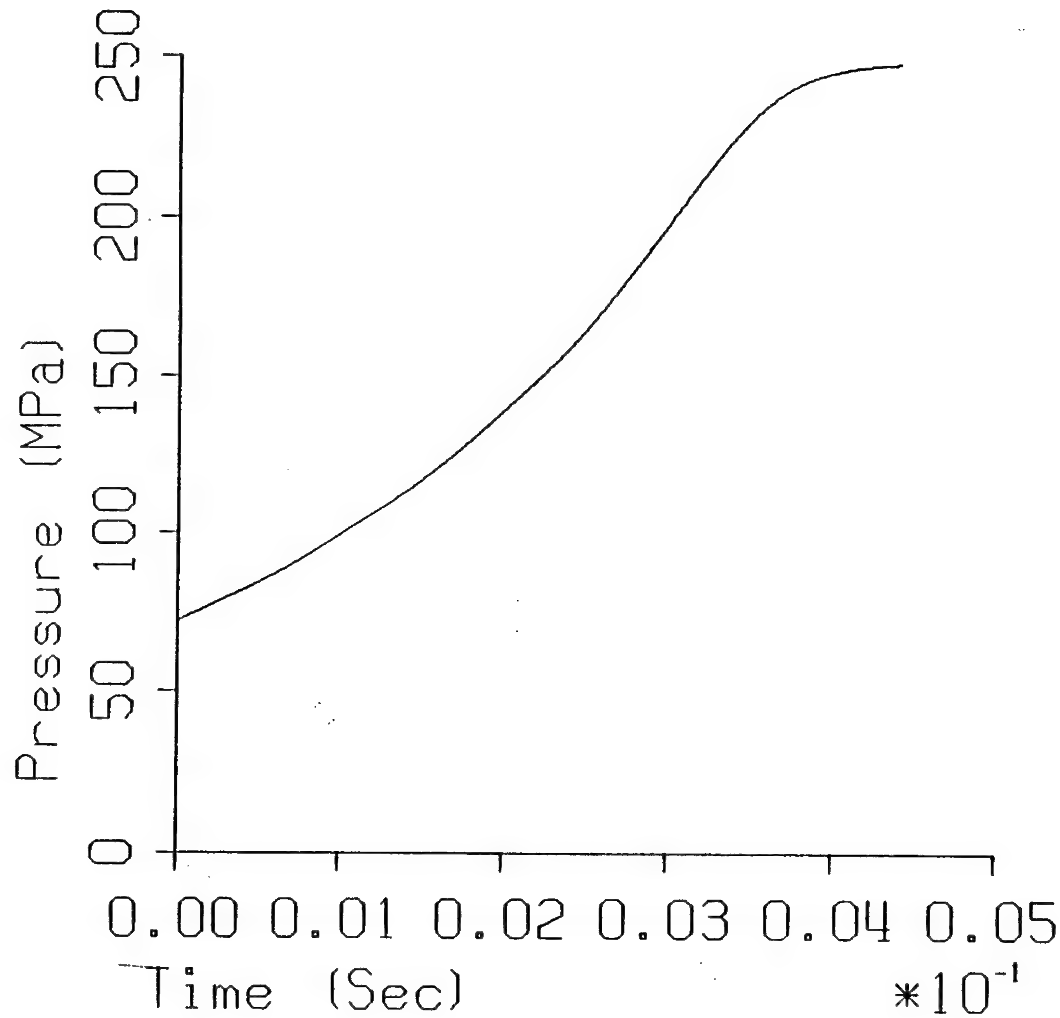

Figure C-6. P/t File SINEOUT.pvt.

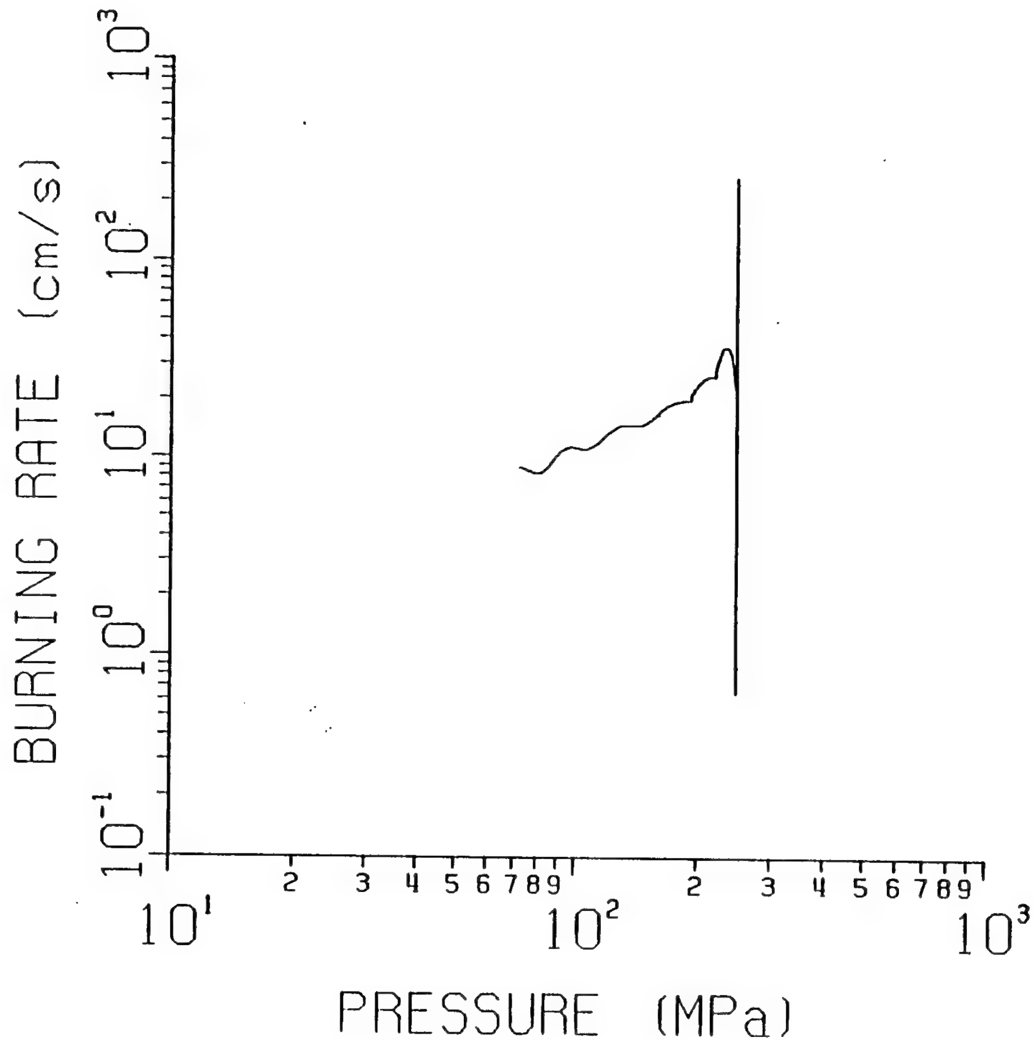

Figure C-7. Burn-Rate Plot SINEOUT.out at 1.14 kHz.

BURNING RATE ANALYSIS
BRLCB V3.0
ADVANCED BALLISTIC CONCEPTS BRANCH - BRL

```
Project : 120CC CLOSED BOMB        Requested by            : DEL GUERCIO
Inf File: SINOUT.inf               Created From .MAS File : JA27PERF.MAS
P/T File: SINOUT.pvt               Calculation Output File: SINOUT.out
Smoothed: SINOUT.pdt               Graphics File           : SINOUT.dat
Fired on:
FIRING REMARKS:
BR CALCULATED WITH "INVBRS7.PVT"ORIGINATED FROM 04255S7
WHICH IS THE JA27PERF BASELINE AT 21.1C

REDUCTION REMARKS:
SINE WAVE SIGNAL ADDED TO  "PT" CURVE BY "SIGNAL.FOR" WITH 2.28kHz FCY.

ITS OUTPUT SIN.OUT OR DAT.IN


                    IGNITER INFORMATION
The Igntier Used Is            : Black Powder          Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

    IGNITER THERMOCHEMICAL PROPERTIES:
Impetus (J/g)          :     290.0 Molecular Weight   :  66.37000
Flame Temperature (K):     2188.0 Covolume (cc/g)    :    .78500
Density (g/cc)         :   1.75000 Gamma              :   1.21840

                   PROPELLANT INFORMATION
The Propellant Used Is           : JA-2 7-PERF GRANULAR Lot: RAD-PE-792-71
The Source For The Propellant Is: RADFORD ARMY AMMUNIT

 Propellant Thermochemical Properties: Following
 Sheets of Output

                   PROPELLANT GRAIN GEOMETRY

Grain Type:7-Perf. Cyl.
        Length --- (cm.):  1.529080
        Outer Diam.(cm.):   .762000
        Perf Diam. (cm.):   .066040
        Inner Web  (cm.):   .130810
        Outer Web  (cm.):   .151130

    Bomb Information                 Gage Information
--------------------------------------------------------
Bomb Type     :Closed Chamber        Gage I.D.     : None
Bomb Vol (cc):      129.4            Input Voltage:    .0000
                                     Constants For Fit: A+Bx+C^2
                                     A:    .00000E+00
                                     B:    .00000E+00
                                     C:    .00000E+00

       Temperature and Charge Mass Information
--------------------------------------------------------
Propellant Mass (g)    :  27.1820     Igniter Mass (g):     .5750
Initial Temp. Prop.(K):  294.        Igniter Temp.(K):  294.
Initial Bomb Temp. (K):  294.
Number of Propellant Grains:    25.72


Number of Wildpoint Passes:   1 Wildpoint Tolerance:  5.000
Number of Smoothing Passes:   1 Smoothing Option:  1
Bridge Length: 15
1 OUTPUT FILE: SINOUT.OP7
 *************************************************************************************


 *************************************************************************************
```

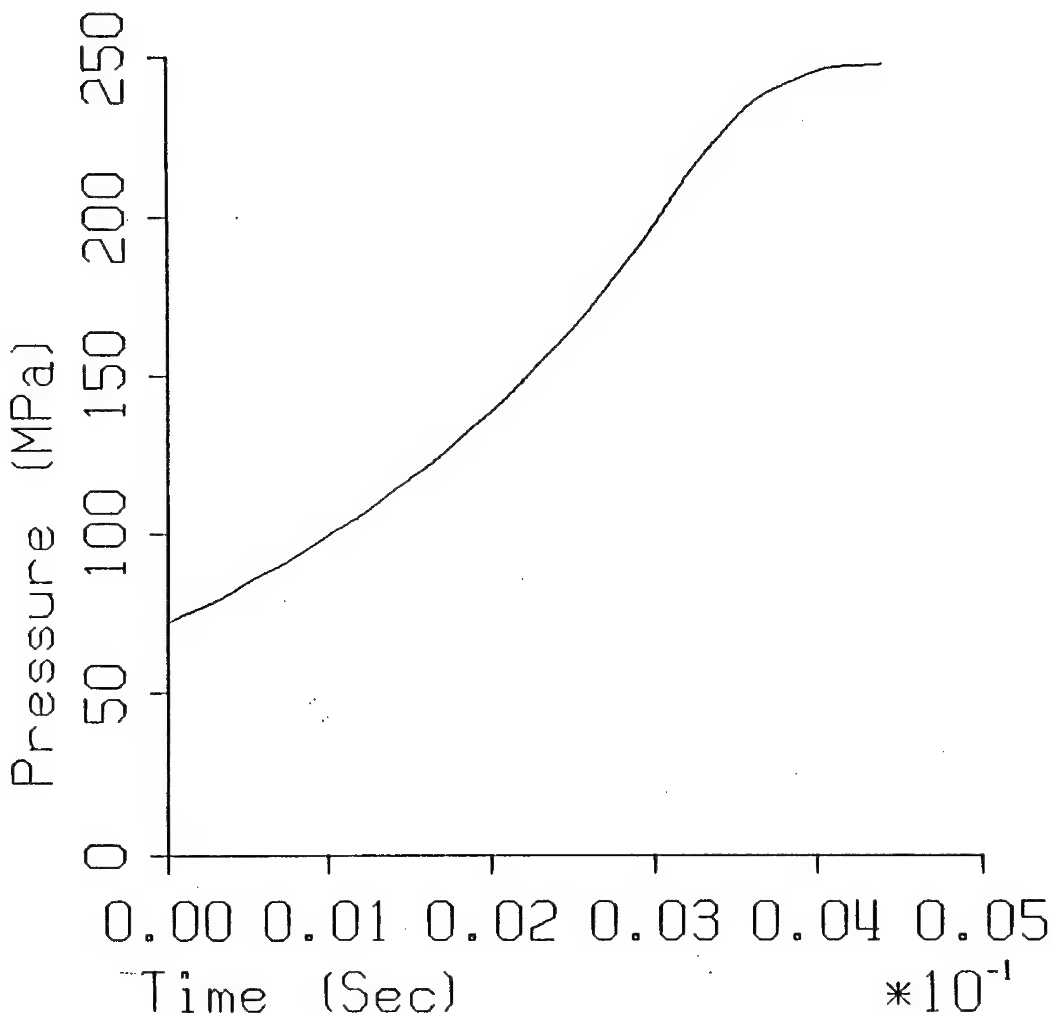

Figure C-8. P/t File SINOUT.pdt.

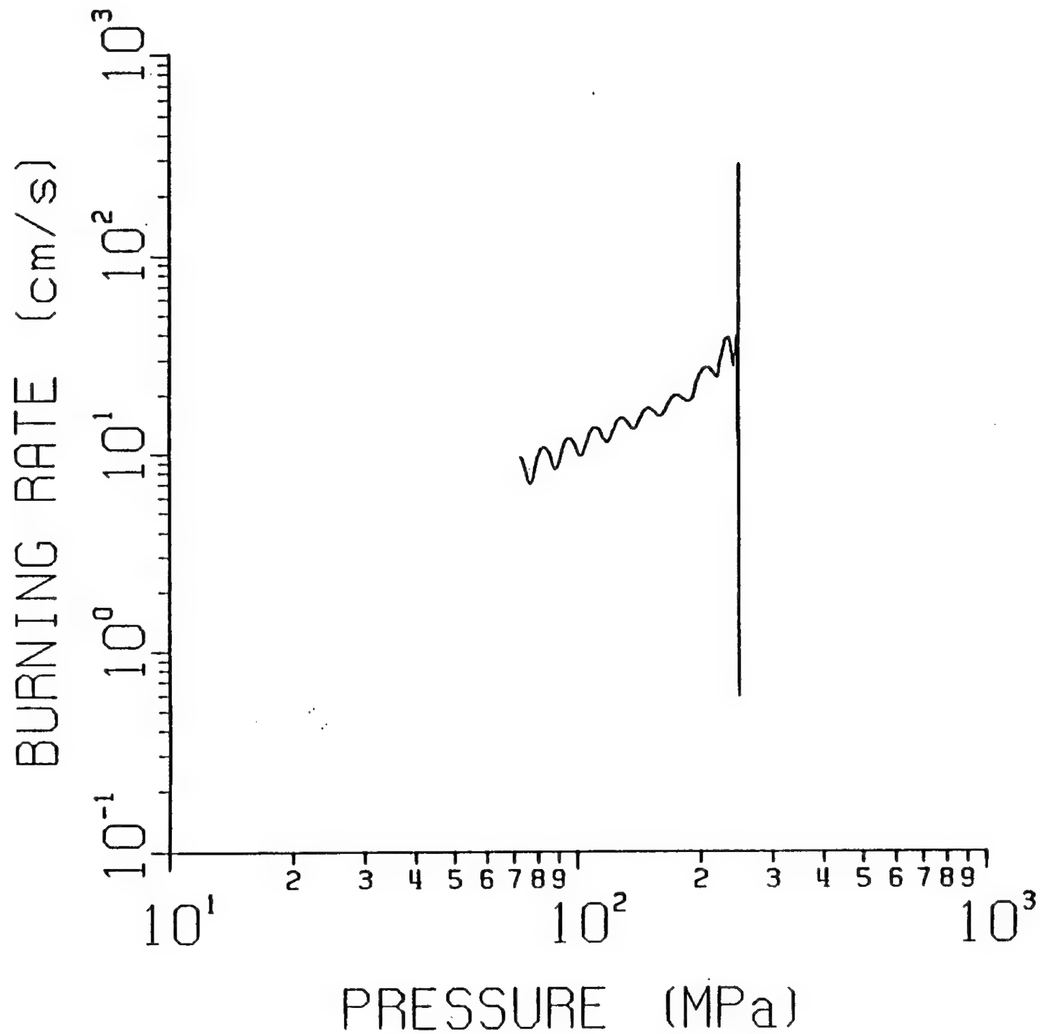

Figure C-9. Burn-Rate Plot SINOUT.out at 2.28 kHz.

ETC BURN RATE ANALYSIS
BRLCB V3.0
ADVANCED BALLISTIC CONCEPTS BRANCH - BRL

```
Project : 120CC CLOSED BOMB       Requested by           : DEL GUERCIO
Inf File: 4125S3.inf              Created From .MAS File : JA27PERF.MAS
P/T File: 4125S3.pvt              Calculation Output File: 4125S3.out
Smoothed: 4125S3.pdt              Graphics File          : 4125S3.dat
EE  File: A:4125S3E.AD
Fired on:
FIRING REMARKS:
NO LPF AT VUPOINT, FFT AT BRLCB 30mHz cutoff fcy

                      IGNITER INFORMATION
The Igntier Used Is          : Black Powder         Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

     IGNITER THERMOCHEMICAL PROPERTIES:
Impetus (J/g)         :    290.0 Molecular Weight  :  66.37000
Flame Temperature (K):    2188.0 Covolume (cc/g)   :    .78500
Density (g/cc)        :  1.75000 Gamma             :   1.21840

                      PROPELLANT INFORMATION
The Propellant Used Is          : JA-2 7-PERF GRANULAR Lot: RAD-PE-792-71
The Source For The Propellant Is: RADFORD ARMY AMMUNIT

 Propellant Thermochemical Properties: Following
 Sheets of Output

                      PROPELLANT GRAIN GEOMETRY

Grain Type:7-Perf. Cyl.
          Length --- (cm.):  1.529080
          Outer Diam.(cm.):   .762000
          Perf Diam. (cm.):   .066040
          Inner Web  (cm.):   .130810
          Outer Web  (cm.):   .151130

     Bomb Information                Gage Information
---------------------------------------------------
Bomb Type     :Closed Chamber        Gage I.D.     : C19928
Bomb Vol (cc):      129.4            Input Voltage:  8.0000
                                     Constants For Fit: A+Bx+C^2
                                     A:    .21637E+00
                                     B:    .54171E-01
                                     C:   -.31853E-06

        Temperature and Charge Mass Information
---------------------------------------------------
Propellant Mass (g)   :  26.9460     Igniter Mass (g):    .0000
Initial Temp. Prop.(K):  322.        Igniter Temp.(K):  294.
Initial Bomb Temp. (K):  294.
Number of Propellant Grains:    25.50


Number of Wildpoint Passes:   1 Wildpoint Tolerance:  5.000
Number of Smoothing Passes:   1 Smoothing Option:  1
Bridge Length: 15
1 OUTPUT FILE: 4125S3.OP7
*********************************************************************************

*********************************************************************************

    Total # Layers =     1

    Chamber Volume (cm3) =   129.400

    Heat-Loss-Fraction (n-d) =       .000

    Time Step (mil-sec) =   .50000000E-02    Max Time Steps =    1200
```

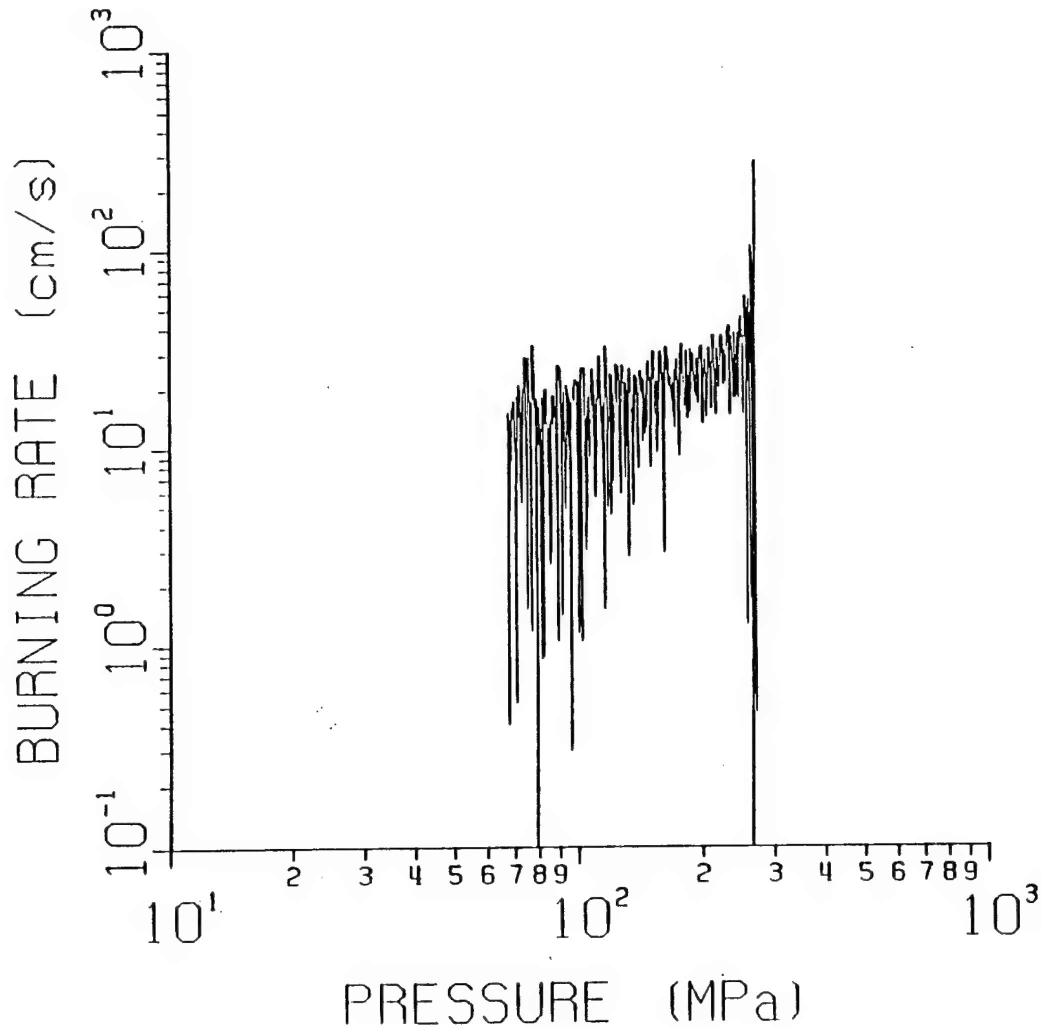

Figure C-10. Burn-Rate Plot 4125S3.out.

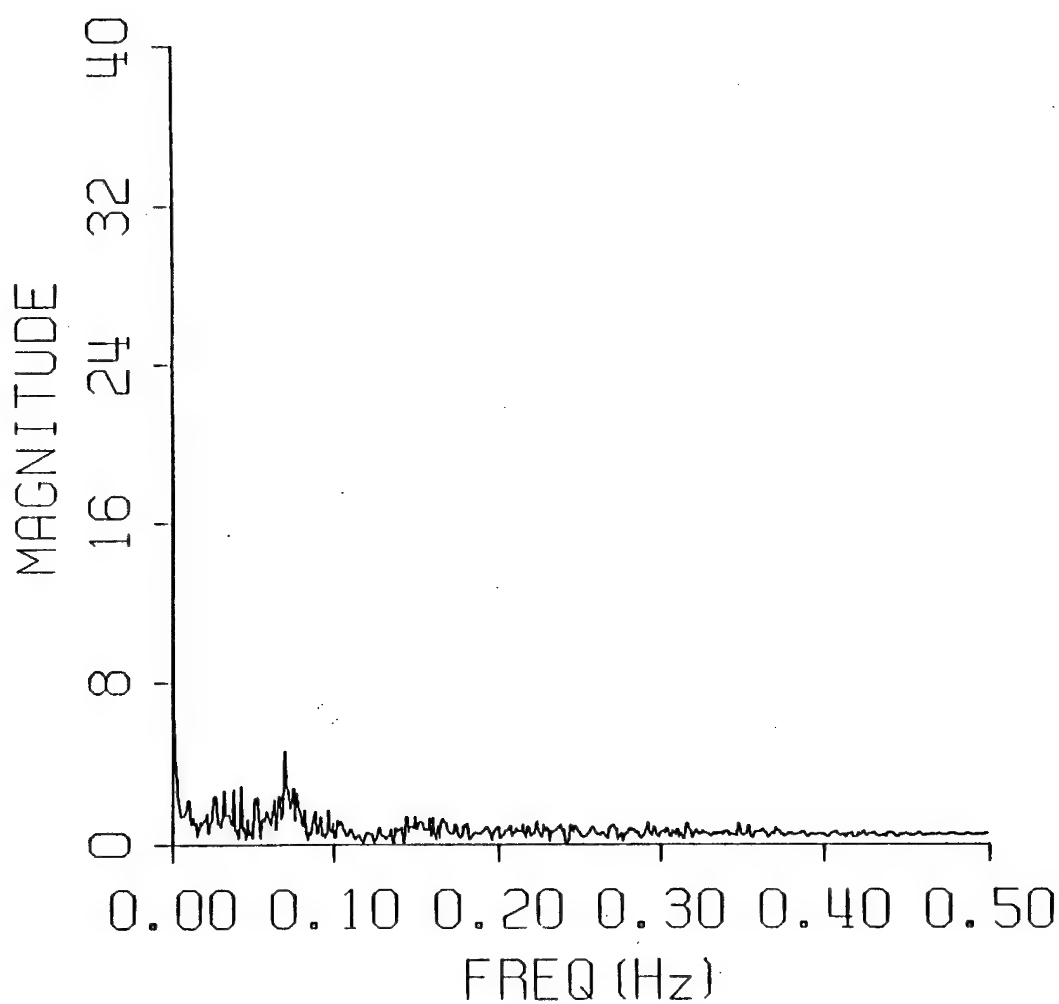

Figure C-11. FFT Spectrum.

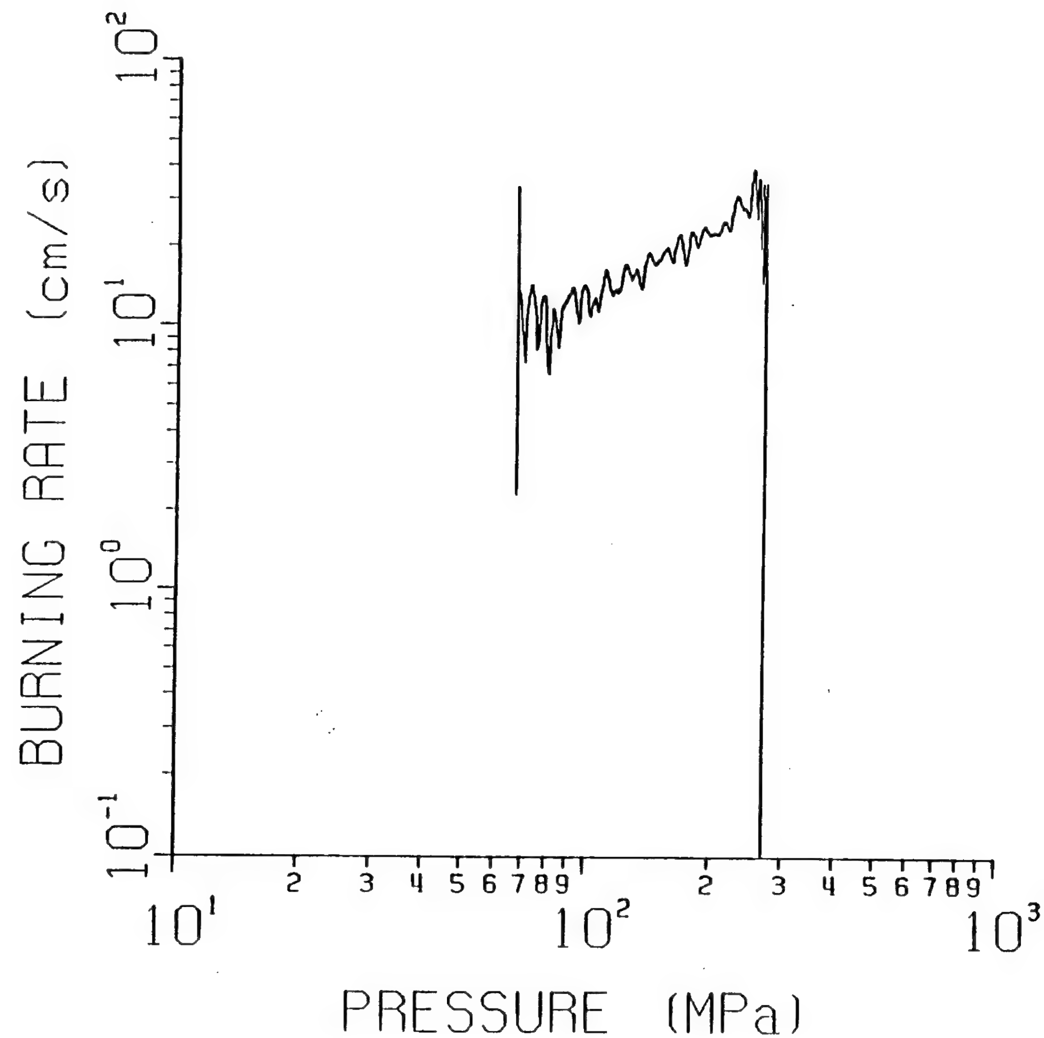

Figure C-12. Burn-Rate Plot 4125S3.out.

ETC BURN RATE ANALYSIS
BRLCB V3.0
ADVANCED BALLISTIC CONCEPTS BRANCH - BRL

```
Project : 120CC CLOSED BOMB       Requested by          : DEL GUERCIO
Inf File: 4115WEGY.inf            Created From .MAS File : JA27PERF.MAS
P/T File: 4115WEGY.pvt            Calculation Output File: 4115WEGY.out
Smoothed: 4115WEGY.pdt            Graphics File          : 4115WEGY.dat
EE  File: B:04115S1E.AD
Fired on: 09/12/96
FIRING REMARKS:
04115S1 REDUCED AS ETC FILE WITH MODIFIED HEAT LOSS% TO
OBTAIN LOCUS OVER BASELINE. H.LOSS INCRESED BY 60% FROM
.20554 TO 0.32886(60% INCREASE)

                    IGNITER INFORMATION
The Igntier Used Is            : Black Powder        Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

     IGNITER THERMOCHEMICAL PROPERTIES:
Impetus (J/g)          :    290.0 Molecular Weight  :  66.37000
Flame Temperature (K):    2188.0 Covolume (cc/g)    :    .78500
Density (g/cc)         :   1.75000 Gamma             :   1.21840

                    PROPELLANT INFORMATION
The Propellant Used Is          : JA-2 7-PERF GRANULAR Lot: RAD-PE-792-71
The Source For The Propellant Is: RADFORD ARMY AMMUNIT

 Propellant Thermochemical Properties: Following
 Sheets of Output

                    PROPELLANT GRAIN GEOMETRY

Grain Type:7-Perf. Cyl.
          Length --- (cm.):  1.529080
          Outer Diam.(cm.):   .762000
          Perf Diam. (cm.):   .066040
          Inner Web  (cm.):   .130810
          Outer Web  (cm.):   .151130

     Bomb Information               Gage Information
--------------------------------------------------
Bomb Type     :Closed Chamber        Gage I.D.     : None
Bomb Vol (cc):       129.4           Input Voltage:    .0000
                                     Constants For Fit: A+Bx+C^2
                                     A:    .00000E+00
                                     B:    .00000E+00
                                     C:    .00000E+00

        Temperature and Charge Mass Information
--------------------------------------------------
Propellant Mass (g)    :  26.9340     Igniter Mass (g):    .0000
Initial Temp. Prop.(K):  294.         Igniter Temp.(K):  294.
Initial Bomb Temp. (K):  294.
Number of Propellant Grains:    25.49


Number of Wildpoint Passes:   1 Wildpoint Tolerance:  5.000
Number of Smoothing Passes:   1 Smoothing Option:  1
Bridge Length: 15
1 OUTPUT FILE: 4115WEGY.OP7
*****************************************************************************************

*****************************************************************************************

    Total # Layers =    1

    Chamber Volume (cm3) =   129.400

    Heat-Loss-Fraction (n-d) =       .000
```

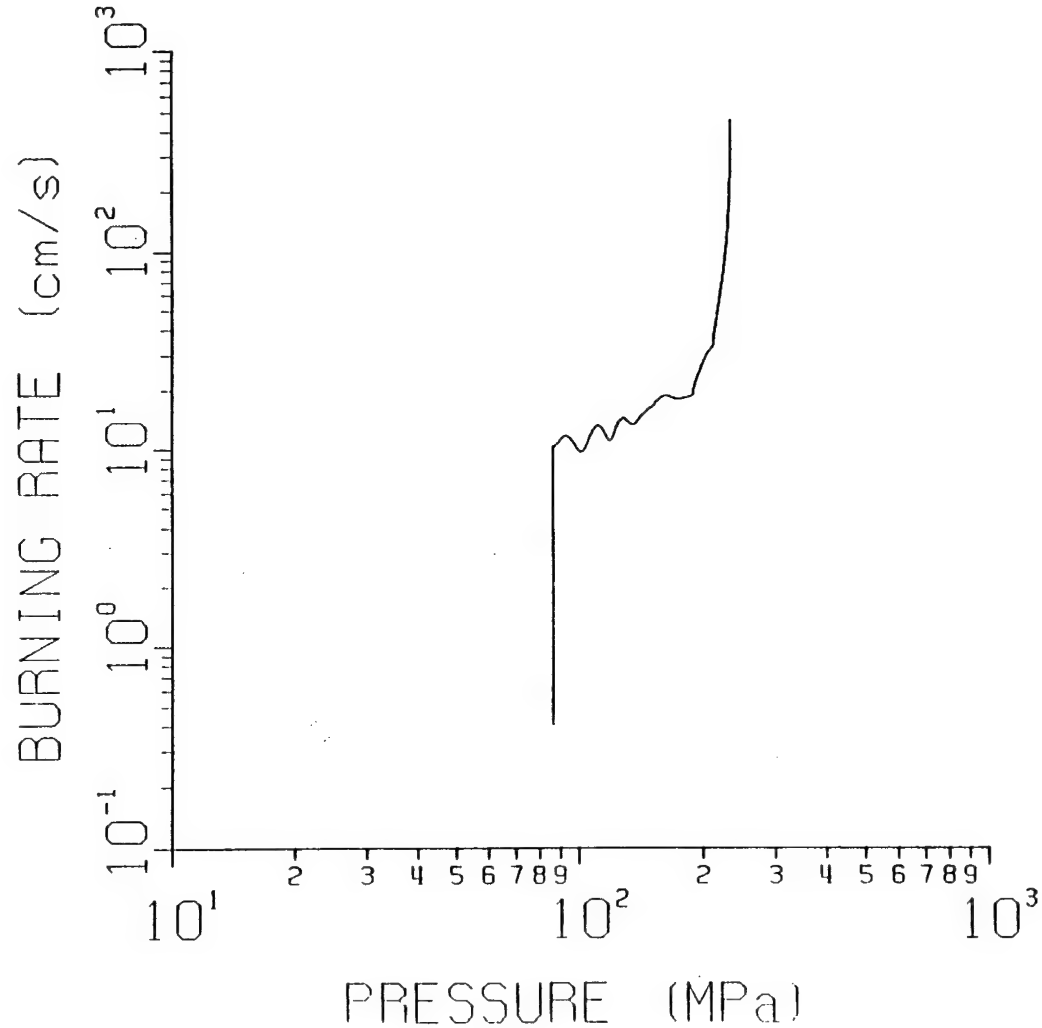

Figure C-13. Burn-Rate Plot 4115WEGY.out.

BURNING RATE ANALYSIS
BRLCB V3.0
ADVANCED BALLISTIC CONCEPTS BRANCH - BRL

```
Project : 120CC CLOSED BOMB      Requested by           : DEL GUERCIO
Inf File: 4115NEGY.inf           Created From .MAS File : JA27PERF.MAS
P/T File: 4115NEGY.pvt           Calculation Output File: 4115NEGY.out
Smoothed: 4115NEGY.pdt           Graphics File          : 4115NEGY.dat
Fired on: 09/12/96
FIRING REMARKS:
USED 4115S1.PVT, ETC FILE,REDUCED AS NON-ETC, WITH ITS ORIGINAL
H.LOSS:0.09230 INCREASED BY 60% TO:0.32886 TO COMPARE ITS
BURN RATE AGAINST IDENT'S 4115WEGY.

                      IGNITER INFORMATION
The Igntier Used Is          : Black Powder         Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

     IGNITER THERMOCHEMICAL PROPERTIES:
Impetus (J/g)          :     290.0 Molecular Weight  :  66.37000
Flame Temperature (K):     2188.0 Covolume (cc/g)   :    .78500
Density (g/cc)         :   1.75000 Gamma             :   1.21840

                      PROPELLANT INFORMATION
The Propellant Used Is          : JA-2 7-PERF GRANULAR Lot: RAD-PE-792-71
The Source For The Propellant Is: RADFORD ARMY AMMUNIT

Propellant Thermochemical Properties: Following
Sheets of Output

                      PROPELLANT GRAIN GEOMETRY

Grain Type:7-Perf. Cyl.
          Length --- (cm.):  1.529080
          Outer Diam.(cm.):   .762000
          Perf Diam. (cm.):   .066040
          Inner Web  (cm.):   .130810
          Outer Web  (cm.):   .151130

     Bomb Information              Gage Information
--------------------------------------------------
Bomb Type    :Closed Chamber       Gage I.D.     : None
Bomb Vol (cc):      129.4          Input Voltage:    .0000
                                   Constants For Fit: A+Bx+C^2
                                   A:     .00000E+00
                                   B:     .00000E+00
                                   C:     .00000E+00

        Temperature and Charge Mass Information
--------------------------------------------------
Propellant Mass (g)   :  26.9340     Igniter Mass (g):     .5000
Initial Temp. Prop.(K):  294.        Igniter Temp.(K):  294.
Initial Bomb Temp. (K):  294.
Number of Propellant Grains:    25.49


Number of Wildpoint Passes:   1 Wildpoint Tolerance:  5.000
Number of Smoothing Passes:   1 Smoothing Option:  1
Bridge Length: 15
1 OUTPUT FILE: 4115NEGY.OP7
*****************************************************************************************

*****************************************************************************************

    Total # Layers =     1

    Chamber Volume (cm3) =   129.400

    Heat-Loss-Fraction (n-d) =       .000
```

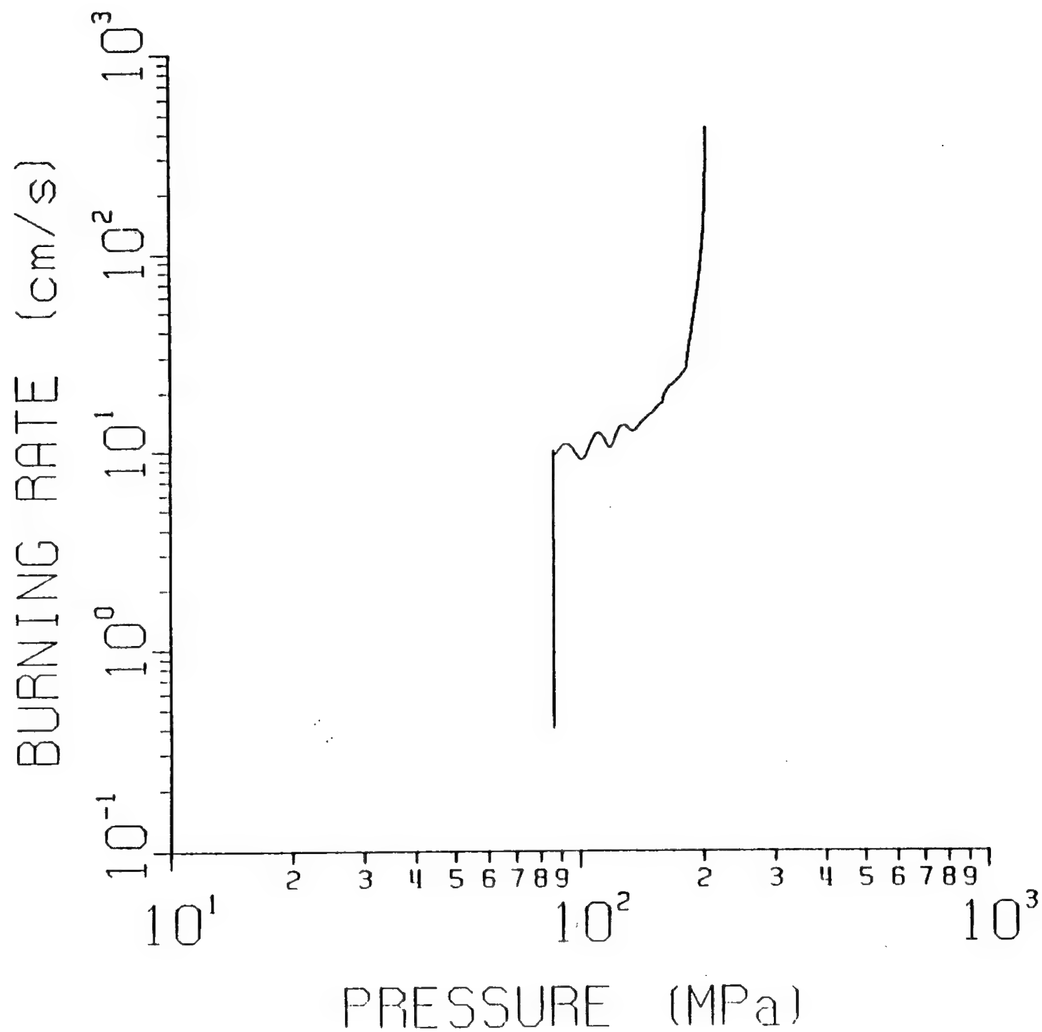

Figure C-14. Burn-Rate Plot 4115NEGY.out.

ETC BURN RATE ANALYSIS
BRLCB V3.0
ADVANCED BALLISTIC CONCEPTS BRANCH - BRL

Project : 120CC CLOSED BOMB
Inf File: 04084S1.inf
P/T File: 04084S1.pvt
Smoothed: 04084S1.pdt
EE File: B:04084S1E.AD
Fired on: RE-DONE11/25/96
FIRING REMARKS:
ETC JA2DIKS AMBIENT AT 36KJ(PFN @ 4KV)
LPF AT VU-POINT @ 2.5kHz

Requested by : DEL GUERCIO
Created From .MAS File : JA2DISK.MAS
Calculation Output File: 04084S1.out
Graphics File : 04084S1.dat

IGNITER INFORMATION

The Igntier Used Is : Black Powder Lot: FFFG
The Source For The Igniter Is: Pellets, Milan Ord.

IGNITER THERMOCHEMICAL PROPERTIES:

Impetus (J/g) :	290.0	Molecular Weight :	66.37000
Flame Temperature (K):	2188.0	Covolume (cc/g) :	.78500
Density (g/cc) :	1.75000	Gamma :	1.21840

PROPELLANT INFORMATION

The Propellant Used Is : JA2 "DISKS" Lot: RAD-PO-292-29A
The Source For The Propellant Is: RADFORD ARMY AMMUNIT

Propellant Thermochemical Properties: Following
Sheets of Output

PROPELLANT GRAIN GEOMETRY

Grain Type:1-Perf. Cyl.
Length --- (cm.): 1.397000
Outer Diam.(cm.): 2.882900
Perf Diam. (cm.): 1.270000
Inner Web (cm.): .806450

Bomb Information

Bomb Type :Closed Chamber
Bomb Vol (cc): 129.4

Gage Information

Gage I.D. : C42442
Input Voltage: 8.0000
Constants For Fit: A+Bx+C^2
A: .75318E-01
B: .63631E-01
C: -.42344E-06

Temperature and Charge Mass Information

Propellant Mass (g) : 28.4220
Initial Temp. Prop.(K): 294.
Initial Bomb Temp. (K): 294.
Number of Propellant Grains: 2.42

Igniter Mass (g): .0000
Igniter Temp.(K): 294.

Number of Wildpoint Passes: 1 Wildpoint Tolerance: 5.000
Number of Smoothing Passes: 1 Smoothing Option: 1
Bridge Length: 15
1 OUTPUT FILE: 04084S1.OP7

****

****

Total # Layers = 1

Chamber Volume (cm3) = 129.400

Heat-Loss-Fraction (n-d) = .000

Time Step (mil-sec) = .20000000E-01 Max Time Steps = 1200

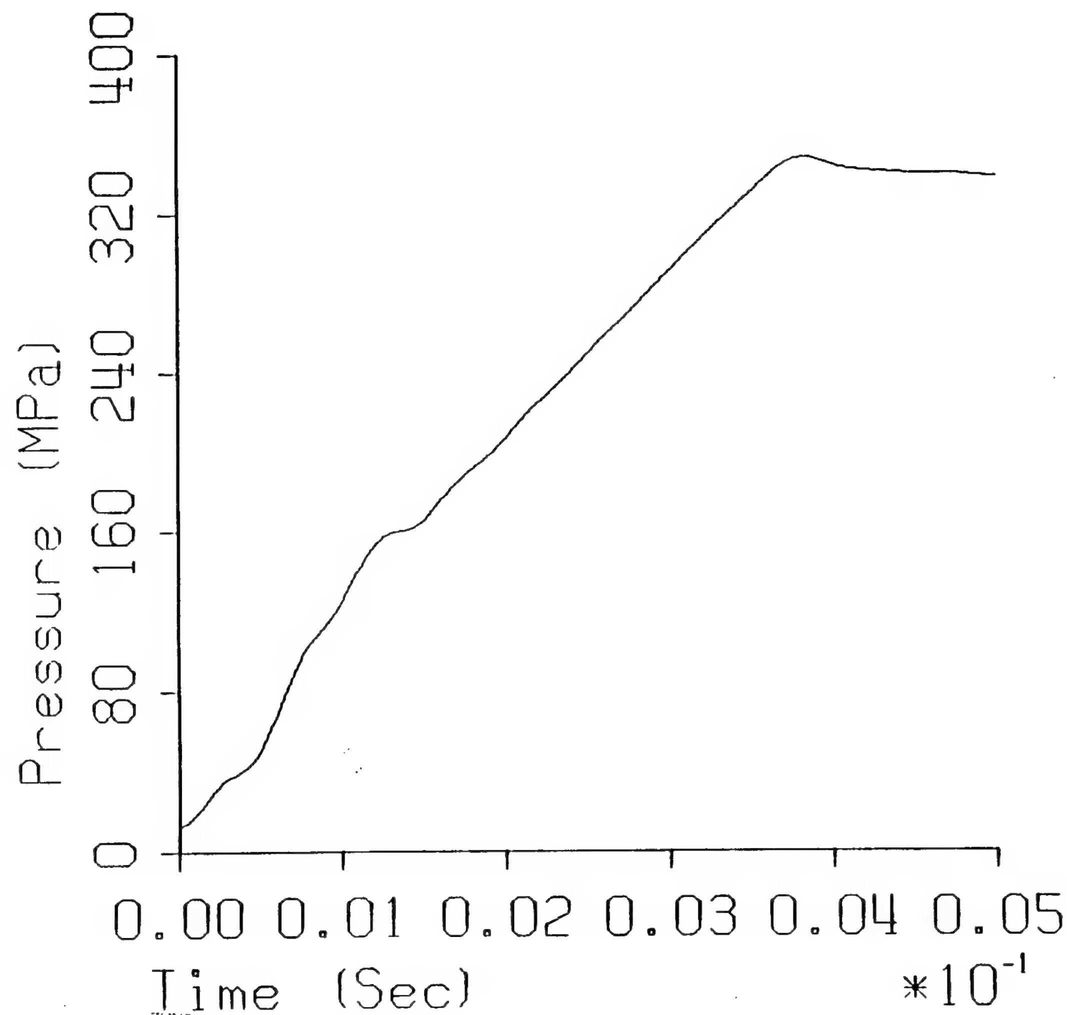

Figure C-15. P/t File 04084S1.pvt.

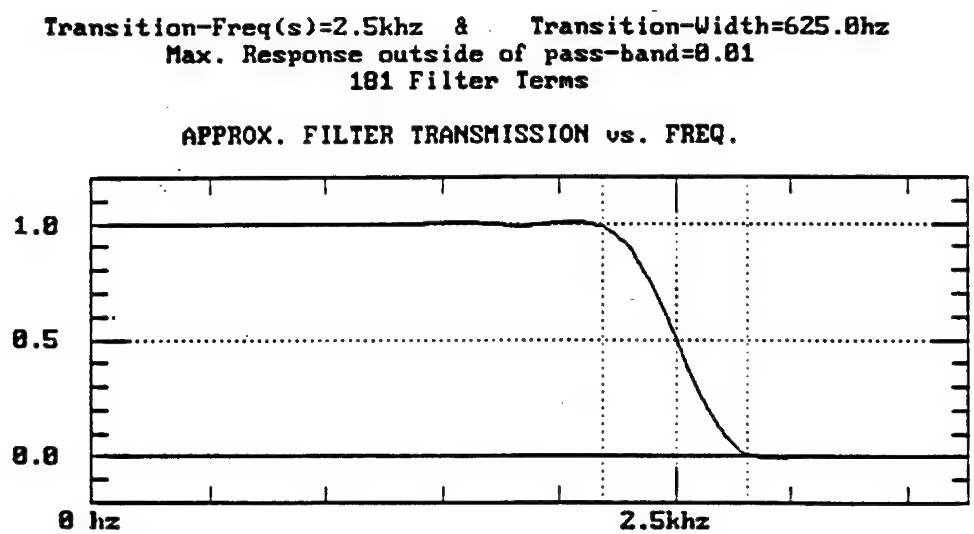

Figure C-16. Summary of LPF Response.

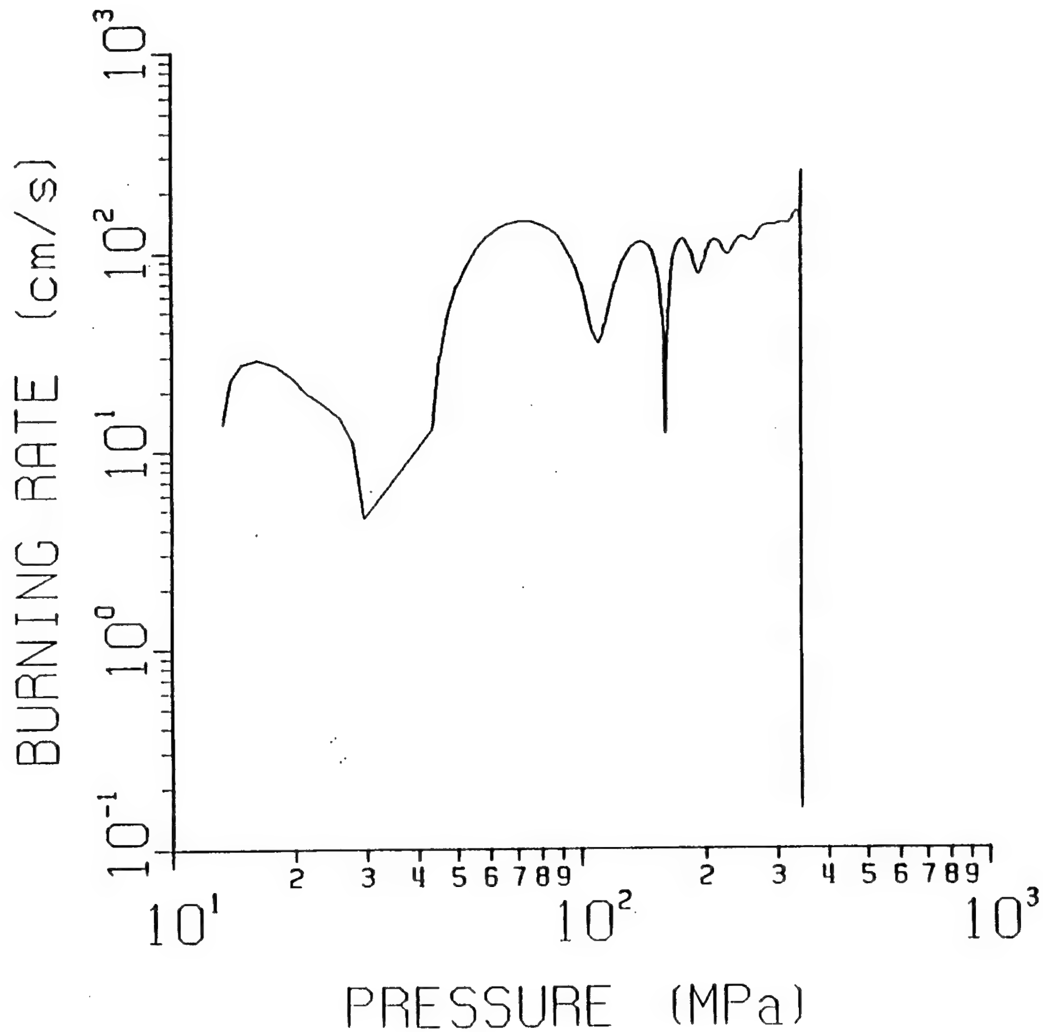

Figure C-17. Burn-Rate Plot 04084S1.out.

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Appendix D:

Vu-Point LPFs and BRLCB FFT Filters

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1. General Characteristics of LPF

The "equiripple" or Chevyshev amplitude approximation[1] is used by Vu-point for the low-pass filtering (LPF) in the time domain of an Infinite Impulse Response (IIR) signal. This approximation is derived from the Chevyshev polynomials, which are a set of orthogonal functions. If the input is represented as:

$$x(t) + u(t),$$

where the first term represents the input signal, and the second represents an undesired signal; the purpose of the filter is to preserve the input signal while eliminating as much of the undesired one as possible. As the filtering process involves a delay and changes to the input signal, the output will be a version of the original signal with an added delay and a possible different amplitude, but with the similar or same shape. If the output of such a filter is expressed as

$$y(t) = Kx(t-\tau),$$

where τ is the delay and K the level change, by taking the Fourier Transforms, the filter is represented in the frequency domain as

$$Y(f) = K\,\epsilon^{-j\omega\tau}\,X(f).$$

When solving for the steady-state transfer function $G(j\omega)$,

$$G(j\omega) = K\,\epsilon^{-j\omega\tau} = K\,\angle{-\omega\tau},$$

[1] Stanley, W. D. "Theory and Principles of Digital Signal Processing." Prentice Hall Inc., 2nd ed., Reston, VA, 1984.

where the amplitude response A(f) and the phase response β(f) are

$$A(f) = K$$

$$\beta(f) = -\omega\tau .$$

An ideal filter then should have a constant amplitude response, while the phase response should be a linear function of the frequency. For filtering to be possible, the spectrum of the unwanted signal must have a different frequency than that of the desired signal, and the amplitude response must also be close to zero in the frequency range of the undesired signal.

As the amplitude and the transfer function can be expressed as

$$G(j\omega) = A(f)\epsilon^{j\beta(f)} = A(f)\angle\beta(f) ,$$

the filter function can be specified by its amplitude response as

$$A^2(f) = G(s)G(-s)\big|_{s=j\omega} .$$

The critical frequencies are determined as "poles" or "zeros" by expressing the amplitude response as

$$A^2(f) = K\frac{c_k\omega^{2k} + ...c_0}{d_k\omega^{2k} + ...d_0} .$$

The transfer function is then determined by the ratio of these polynomials in which the critical frequencies are expressed as poles or zeros, multiplied by the gain constant k.

For the Chebyshev filter the amplitude response is defined as

$$A^2(f) = \frac{\alpha}{1 + \epsilon^2 C_k^2(\omega/\omega_c)},$$

where $C_k(x)$ denotes the Chebyshev polynomial (Figures A-1 and A-2); α, the dc gain level; and ϵ^2, the passband ripple. The frequency f_c corresponding to the radian frequency ω_c is the cutoff frequency. The frequency f_c is the highest value at which the passband ripple determines the response of the filter, and in relation to the amplitude in dB is

$$r = 10 \log_{10} \frac{A^2 \max}{A^2 \min}$$

The passband is the range on which the ripple oscillates from dc to f_c. The filter can be designed with different ripple orders (i.e., 0.5-dB, 1-dB, 2-dB, and 3-dB ripple). As the passband ripple increases, for a given number of poles, the stopband attenuation will also increase. Vu-point uses $\alpha = 1$, which adjusts the maximum gain to unity. There is a tradeoff between the allowable passband ripple (Figure D-3) and the stopband attenuation. The magnitude of the frequency response is either equiripple in the passband and monotonic in the stopband (LPF case) or monotonic in the passband and equiripple in the stopband giving both a lower order filter. A typical Vu-point LPF response is seen in Figure D-4.

The stopband amplitude response of a Chevyshev filter with a ripple order of 0.5 dB can be seen on Figure D-5. The functions shown provide the stopband amplitude response from two to seven poles. As the number of poles decreases, the slope of the function from the cutoff frequency point (normalized frequency = 1) becomes less sharper increasing the transition band and decreasing the stopband, making the filter less effective.

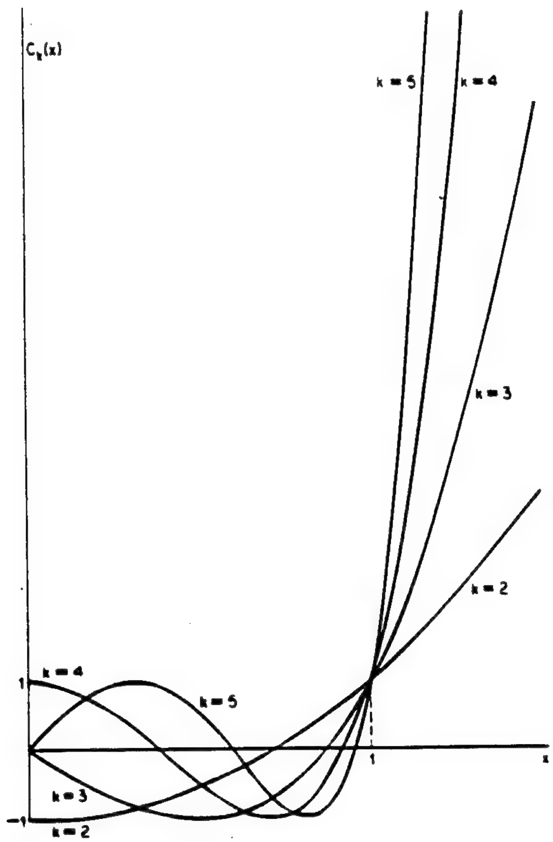

Figure D-1. Forms for Several of the Chebyshev Polynomials.

k	$C_k(x)$
1	x
2	$2x^2 - 1$
3	$4x^3 - 3x$
4	$8x^4 - 8x^2 + 1$
5	$16x^5 - 20x^3 + 5x$
6	$32x^6 - 48x^4 + 18x^2 - 1$

Figure D-2. Chebyshev Polynomials.

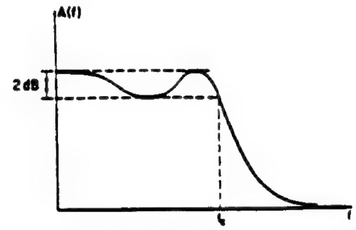

Figure D-3. Chebyshev Amplitude Response for Values of k = 3 and Passband Ripple of 2 dB.

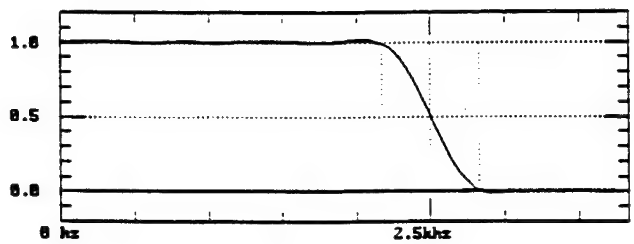

Figure D-4. Vu-Point LPF Response With 2.5 kHz Transition Frequency, 665.71 Hz Transition Width, and 0.01 Maximum Response Outside of Passband.

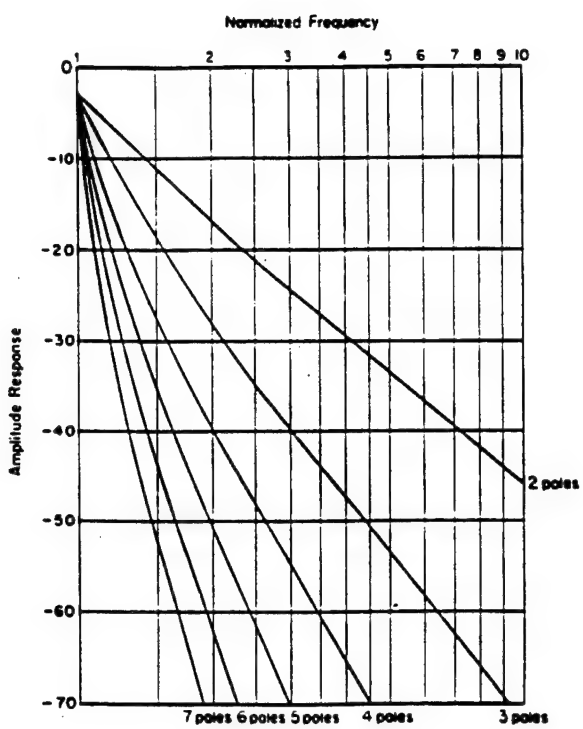

Figure D-5. Stopband Amplitude Responses of a 0.5-dB Chebyshev Ripple Filter.

2. Characteristics of the FFT

The finite impulse response (FIR) digital filter implementation through the FFT has an ideal linear phase, but requires higher order functions than the ones used for the IIR case. By sampling the Fourier transform of the signal, its discrete Fourier transform (DFT) is originated,[1] which can then be conveniently calculated by algorithms like FFT. As a window function is applied to this DFT by convolution in the frequency domain, a filtered signal is obtained. These windows have the property that their Fourier transforms are concentrated about $\omega = 0$. Some of the windows typically used are Rectangular, Barlett, Hanning, Hamming, and Blackman. The Rectangular window has the sharpest transition, but the others offer a smoother tapering effect to zero. The Fourier transform of a continuous time function x(t) is generally expressed as

$$X(f) = \int_{-\infty}^{\infty} x(t)\ \epsilon^{-j\omega t}\ dt\,.$$

The DFT can be defined as a sequence rather than function of a continuous variable. It is formed by samples equally spaced in frequency of the Fourier transform of the signal. As a sequence, it can be represented as

$$x[n] = \frac{1}{2\Pi}\int_{-\Pi}^{\Pi} X(\epsilon^{j\omega})\ \epsilon^{j\omega n}\ d\omega\,,$$

where

$$X(\epsilon^{j\omega}) = \sum_{n=-\infty}^{\infty} x[n]\ \epsilon^{-j\omega n}\,.$$

[1] Oppenheim, A. V. "Discrete-Time Signal Processing." Prentice Hall Inc., 3rd ed., Englewood Cliffs, NJ, 1989.

Given an aperiodic sequence x(n) with Fourier transform $X(\varepsilon^{j\omega})$, a sequence X[k] can be expressed by sampling $(\varepsilon^{j\omega})$ at frequencies $\omega_k = 2\pi k/N$, where

$$X[k] = X(\epsilon^{j\omega})|_{\omega = (2\Pi/N)k} \cdot$$

The Fourier series expression can be written as

$$x[n] = \frac{1}{N}\sum_k X[k] \ \epsilon^{2\Pi/N) \ kn} = \frac{1}{N}\sum X(k)W_N^{-kn} .$$

Since the Fourier transform is periodic in ω with period 2π, the final sequence is also periodic in k with period N. The Fourier transform of an aperiodic sequence can then be expressed as the discrete Fourier series of a periodic sequence. The sequence of DFS coefficients X[k] of the periodic sequence x(n) is also a periodic sequence of period equal to N. By selecting these Fourier coefficients as a finite sequence corresponding to one period of X[k], the duality between the time domain and the frequency domain is maintained. This finite sequence is defined as the DFT. Figure D-6 shows the continuous time signal s(t) converted into a sequence x(n) and multiplied by the window function w[n] to generate the finite length DFT.

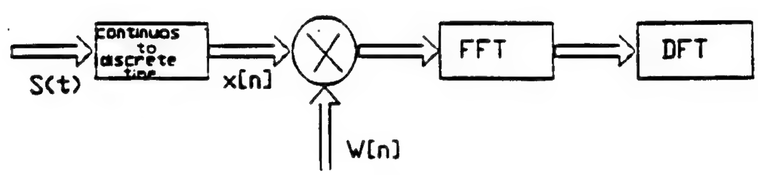

Figure D-6. DFT of a Signal.

The Fourier transform X(f) can be expressed in terms of its amplitude and phase as

$$X(f) = |X(f)|\epsilon^{/\theta f} .$$

A plot of $|X(f)|$ vs. f (Figure D-7) is referred as the amplitude spectrum of x(t), and a plot of $\angle X(f)$ vs. f as the phase spectrum.

The energy E of the signal x(t) can be expressed (Parseval's theorem) as

$$E = \int_{-\infty}^{\infty} |x(t)|^2 dt = \int_{-\infty}^{\infty} |X(f)|^2 df.$$

The energy spectral density of the signal **x(t)** is then defined as

$$G(f) = |X(f)|^2.$$

The total energy of a signal can then be calculated by integrating G(f) overall frequency.

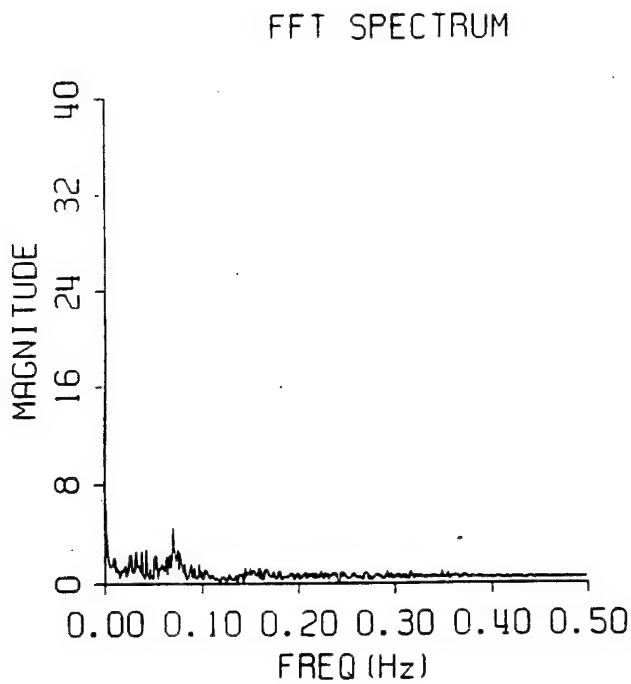

Figure D-7. BRLCB Amplitude Spectrum Plot of $|X(f)|$ vs. f.

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Closed-chamber electrothermal-chemical firings of JA2 7-perf propellant revealed the presence of oscillations on its burn rates. This study was originated by questions raised about the probable causes for this phenomena. The discussion that follows analyses the fiber-optic links utilized for the data acquisition, the code used to deduce the propellant burn rate and the filtering for data smoothing, and finally, the effect of the plasma injection and its energy. The result of this analysis suggests that the plasma injection contributes to burn-rate oscillations, that their amplitude is proportional to the energy of the plasma injected, and that the oscillations are a function of the closed-chamber pressure.

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